Validation of the Fish Community Index of Estuarine Condition and development of a monitoring regime for the Swan-Canning Riverpark

Final report

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The funds for this project were kindly provided by the Swan River Trust and Murdoch University. Gratitude is also expressed to the many colleagues at the Centre for Fish, Fisheries and Aquatic Ecosystems Research, Murdoch University, who have helped with sampling the fish fauna of the Swan-Canning Estuary, both historically and during the current study. We also thank the Swan River Trust for supplying water quality and phytoplankton data/reports from the Swan-Canning Estuary, and Professors Ken Pollock and Ian Wright for invaluable statistical advice.

Executive Summary

A three-year study by Murdoch University (2007-2010), which was funded by the Swan River Trust (SRT), Department of Water (DoW) and Department of Fisheries (DoF), developed indices for assessing the ecological condition of the Swan-Canning Estuary based on characteristics of its fish assemblages.

These Fish Community Indices were developed for the nearshore, shallow waters of the estuary and also for its deeper, offshore waters. They integrate information on various biological variables (metrics), each of which quantifies an aspect of the structure and/or function of estuarine fish communities and responds to a wide array of stressors affecting the ecosystem. Given the well-known responses of these fauna to environmental stressors, these fish-based indices therefore provide a means to assess an important component of the ecology of the system and how it responds to changes in estuarine condition.

The present report describes a follow-up study which aimed to validate index sensitivity and robustness and to develop a monitoring regime to enable the condition of the Swan-Canning Estuary to be reliably quantified and reported into the future. The scope of this report was extended in 2012 to include a review of alternative approaches for determining estuarine condition grades/categories.

Sampling of nearshore and offshore fish assemblages was performed once in each of the middle and final months of both summer and autumn 2011 at various sites throughout the estuary, and the resulting fish abundance data were used to calculate Fish Community Index scores. Patterns in these scores were then analysed to determine the appropriate intensity of spatial sampling (*i.e.* number of replicate sampling sites per ecological management zone) and the optimum timing and length of the sampling period required for any future monitoring regime.

The results of these analyses showed that, for both the nearshore and offshore indices, a future monitoring regime should employ a minimum sampling intensity of six sites per zone to provide an adequate level of replication for detecting significant changes in ecological condition of the Swan-Canning Estuary.

Considerable changes in index scores from month to month were observed for some individual sites. However, at the broader scale of estuarine zones (*i.e.* the scale at which the indices were developed and intended for use),

intra-seasonal changes in mean index scores were less pronounced and did not result in a change in the provisional condition status of any zone in either season. On a yet broader scale, the mean index scores across the whole estuary changed very little between months, demonstrating the robustness of the indices to natural variability in fish community composition.

This study also demonstrated the sensitivity of the indices to perturbations caused by short-term, spatially discrete algal (*Karlodinium veneficum*) blooms that occurred in the Canning Estuary in May 2011 and historically in the Swan River in March 2004. Analyses of index scores from samples collected before, during and after these blooms showed that, in both cases, index scores at sites within bloom-affected areas exhibited a clear decrease from pre-bloom conditions, and a subsequent recovery after the bloom had collapsed. Together, these findings suggest that the nearshore and offshore indices are sufficiently sensitive to quantify ecological condition responses to local-scale environmental perturbations such as algal blooms, and to track the subsequent recovery of the system following their removal.

The offshore waters of the Swan River, in particular, were observed to have suffered a marked decline in ecological condition during the March 2004 *K. veneficum* bloom. By examining changes in the scores from the nearshore and offshore indices together, it has been demonstrated that nearshore habitats within the Swan-Canning Estuary provide crucial refuges for fishes during significant algal bloom events.

It should be noted that the measurement of water quality parameters at night would improve our understanding of the factors affecting fish (and therefore Fish Community Index) responses to algal bloom events.

A comparative evaluation of alternative systems for determining estuarine condition grades was also performed during this study. This aimed to determine which of three alternative approaches, applied to the offshore and nearshore indices and employing historical data sets of observed index scores, would provide the optimal grading system for the Fish Community Indices of estuarine condition.

The three approaches included a ‘distribution test classification system’ – a descriptive system using statistical tests to compare ecological condition against that which has been observed historically – and two percentile-based, alphanumeric (A-E) grading systems. The latter were an ‘equal quintile-based grading system’, in which grade boundaries were determined by dividing the distribution of historical index scores into five equal quintiles, and an ‘unequal quantile-based grading system' in which the respective boundaries for grades A and E comprised the 90th and 10th percentiles of the distribution of historical index scores and the intermediate grades B-D were determined by dividing the remaining 80% of historical index scores into three equal quantiles.

The ensuing condition grades awarded under each system to samples in a validation set collected during 2011-12 were analysed to assess the robustness and apparent sensitivity of the resulting indices. Overall, the alphanumeric grading system based on unequal quantiles of the distribution of scores in the full historical data set provided the most robust yet sensitive grading scheme and is thus proposed as the optimal approach for future implementation of both the offshore and nearshore indices.

The findings from this study have informed the design of a rigorous, practicable and relatively low cost monitoring regime for the future implementation of these indices as a management and communication tool. The proposed monitoring regime is described in detail, including an account of each step in the process of index implementation, from the sampling design and collection of data, via the calculation of metric and index scores, to the presentation, interpretation and communication of index results.

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1. Introduction

1.1. Background and rationale

In response to increasing pressures on the Swan-Canning Riverpark, the Swan River Trust (SRT) and other management agencies have, in recent years, sought to improve the degree to which the condition of this ecosystem is measured, acted upon and reported to the community. Indicators, which may be defined as ‘signs or signals that relay a complex message, from potentially numerous sources, in a simple and useful manner’ (Jackson et al. 2000), are a key tool for achieving these management and community reporting objectives.

A 2007-2010 study, which was funded by the SRT, Department of Water (DoW), Department of Fisheries (DoF) and Murdoch University, sought to develop biological (fish-based) indicators for assessing and monitoring the ecosystem condition of the Swan-Canning Estuary (Valesini et al. 2011). Biological, or biotic, indicators provide the most ecologically relevant measures of the overall health of an ecosystem as they reflect both the integrated condition of the various structural components of that system and their complex functional processes and interactions. One such indicator that was developed during the former study is a multimetric index based on fish assemblage characteristics (Hallett 2010). Multimetric indices comprise information on various characteristics (metrics), each of which quantifies an aspect of the structure and/or function of the biological assemblage on which they are based. Such indices thus respond to the wide array of stressors affecting the ecosystem. The multimetric Fish Community Indices developed by Hallett (2010) therefore provide a means to assess an important component of the ecology of the system and how it responds to changes in estuarine condition.

The rationale for using biotic indices to assess the ecological condition of estuaries is widely documented and has become incorporated into environmental legislation worldwide (Borja et al. 2008, Hering et al. 2010). Essentially, with increasing anthropogenic (human-induced) degradation of estuarine ecosystems, those fish species that have specific habitat, feeding or other environmental requirements will become less abundant and diverse, whilst those with more general requirements become more abundant and diverse, leading to an overall reduction in fish species diversity (Quataert et al. 2011). Thus, in a degraded estuary with poor water, sediment and habitat quality, the abundance and diversity of specialist feeders (*e.g.* Garfish and Tailor), benthic-associated species (*e.g.* Cobbler and Flathead) and estuarine spawning species (*e.g.* Perth herring and Yellow-tail grunter) – and therefore also the overall number and diversity of species – will decrease due to loss of their particular, requisite conditions, whilst generalist feeders (*e.g.* Banded toadfish or blowfish) and detritivores (*e.g.* Sea mullet) will become more abundant and dominant (left side of Fig. 1). The reverse will be observed in a relatively undegraded system which is subjected to fewer human stressors (right side of Fig. 1; noting that this Figure represents a continuum of ecological condition).

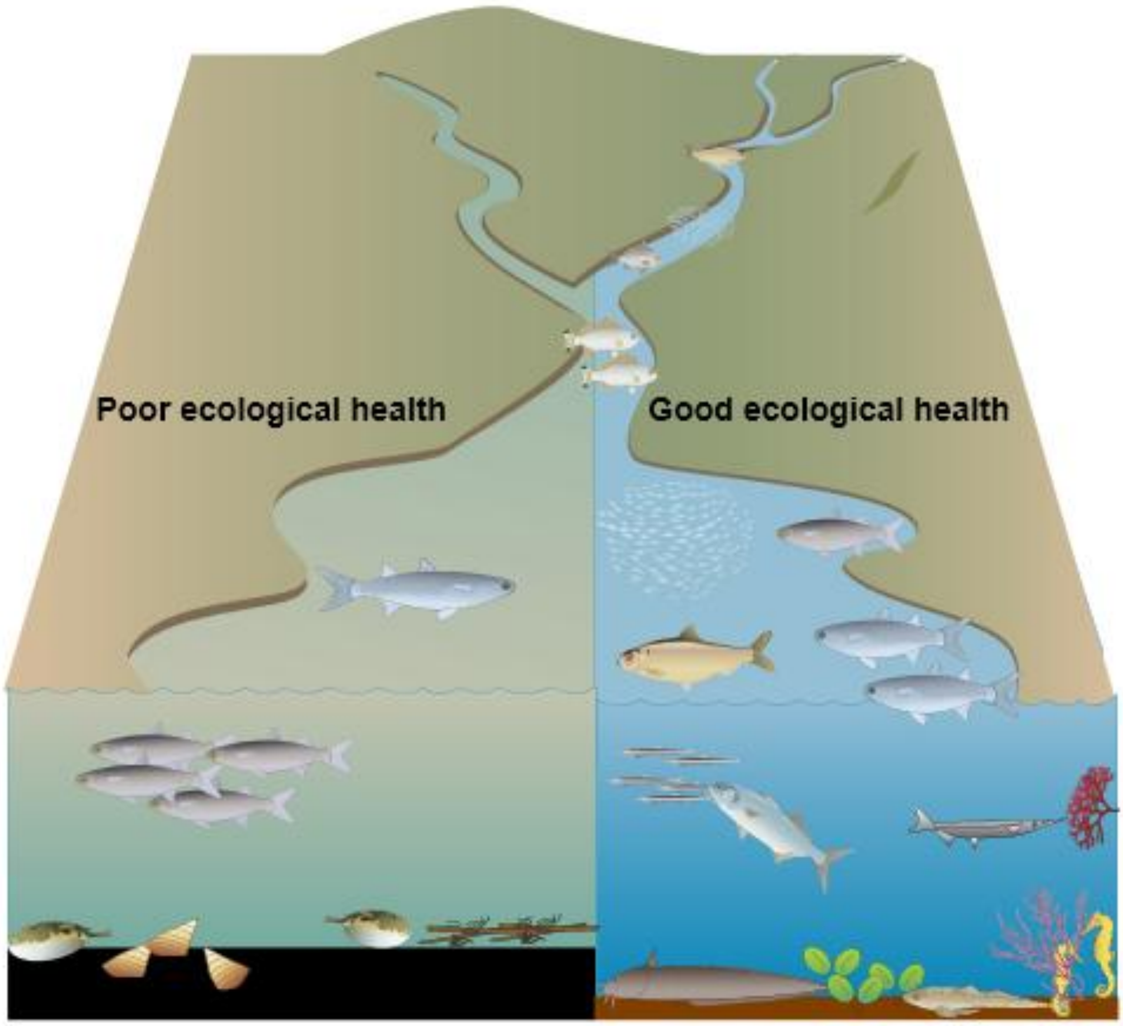


Figure 1. Conceptual diagram illustrating the predicted responses of the estuarine fish community to situations of poor and good ecological condition (images courtesy of the Integration and Application Network [ian.umces.edu/symbols/]).

1.2. Development of the Fish Community Indices

The multimetric Fish Community Indices that were developed for assessing the condition of nearshore (<2 m depth) and offshore (>2 m depth) waters of the Swan-Canning Estuary by Hallett (2010) are the first to be produced for Western Australian estuaries. These indices were developed via an accepted framework that involved the following key stages (summarised in Fig. 2 – see Hallett [2010] for further details).

- **Identify appropriate candidate fish metrics.** An extensive range of potential fish community metrics were initially tested for their suitability for incorporation into the indices. These metrics included various measures of species composition, diversity and abundance, trophic and functional aspects of the assemblage, *i.e.* the contributions of different habitat, feeding mode and life-history (estuarine use) guilds and, where relevant, 'sentinel' (indicator) species.
- **Select best subset of candidate metrics.** Novel, objective statistical approaches were employed to identify the metrics which were most sensitive to inter-annual changes in ecosystem condition. Sets of 11 and seven metrics were selected for assessing the condition of nearshore and offshore waters of this system, respectively (Table 1).
- **Establish best available reference conditions for each metric.** Reference conditions for each selected nearshore and offshore metric, representing the 'best available' values against which the previous, current and future condition of the Swan-Canning Estuary could be assessed and compared, were then established for each season and region of the estuary using 30 years of fish assemblage data recorded throughout the system.
- **Calculate metric scores.** Metric scoring thresholds were then determined statistically from the nearshore and offshore fish assemblage data sets, enabling each metric in each sample to be scored according to the extent of its deviation from the relevant reference condition.
- **Calculate index scores.** Index scores for nearshore or offshore Fish Community Indices were calculated by summing the scores for their component metrics and then adjusting the resultant value by the number of metrics in the index to produce a final, easily interpretable index score for each site, ranging from 0-100. These site scores may then be averaged to provide a quantitative measure of the condition of specific estuarine zones, and/or of the estuary as a whole. Thresholds for establishing the qualitative condition of the site/zone/estuary (*i.e.* good, fair, poor, very poor) were also determined by subdividing the possible range of index scores into four classes of equal breadth[1].
- **Validate index performance.** The reliability of the nearshore and offshore indices was evaluated by quantifying the variability of index

[1] Please note that further work has since been undertaken to review this provisional grading system for the indices, including a comparative evaluation of alternative grading systems (see below and section 4 of this report).

scores among replicate sites, within and between seasons and between consecutive years. Classification of the condition status of the estuary was shown to be fairly robust, despite the effects of both natural spatio-temporal variability and sampling error on index scores. The consistently lower spatial variability of nearshore and offshore index scores recorded in summer and autumn indicated that these seasons might represent a suitable period for future monitoring of the ecological condition of the Swan Estuary, and thus informed the timing of the current study.

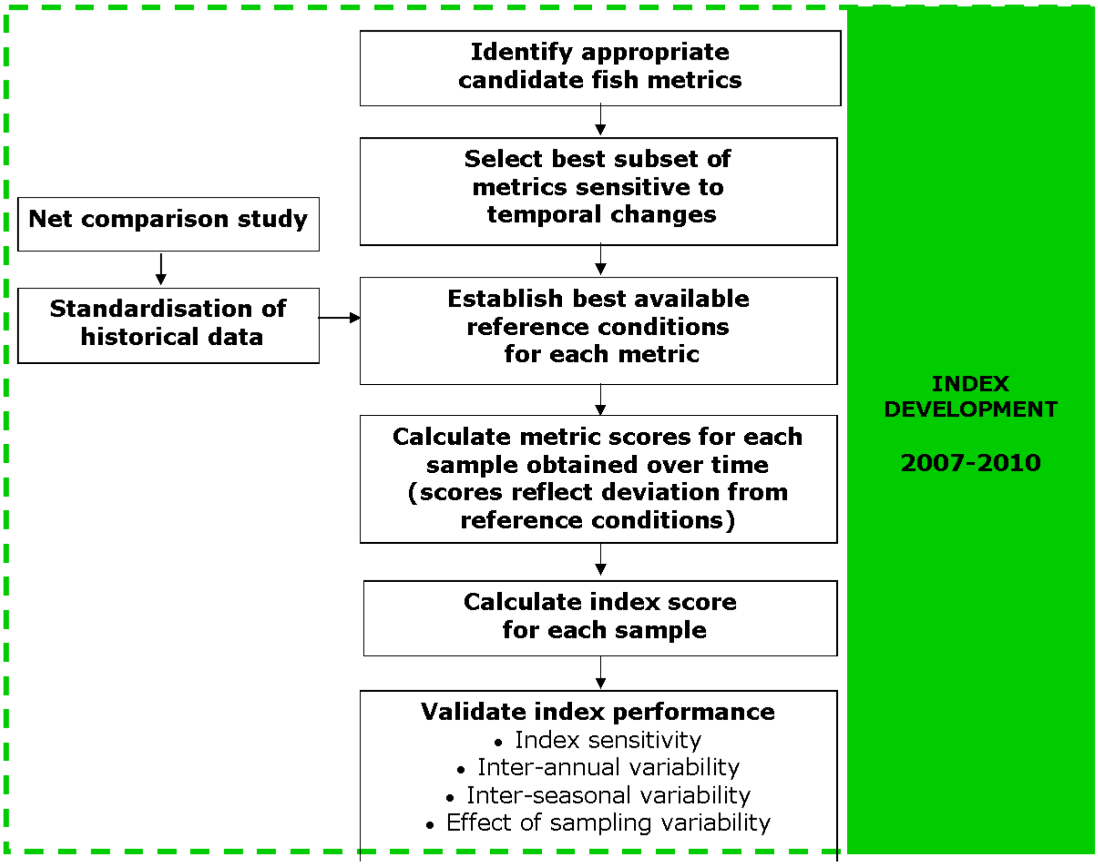


Figure 2. Summary of the stages in the development of multimetric Fish Community Indices for the Swan-Canning Estuary (Hallett 2010).

Table 1. Summary of the fish metrics selected (✓) for the nearshore and offshore Fish Community Indices developed for the Swan-Canning Estuary (Hallett et al. 2012a).

Metric	***Nearshore Index***	***Offshore Index***
Number of species	✓	✓
Dominance		
Shannon-Wiener diversity		✓
Proportion of trophic specialists	✓	
Number of trophic specialist species	✓	✓
Number of trophic generalist species	✓	✓
Proportion of detritivores	✓	✓
Feeding guild composition		
Proportion of benthic-associated individuals	✓	✓
Number of benthic species	✓	
Proportion of estuarine spawning individuals	✓	✓
Number of estuarine spawning species	✓	
Proportion of *Pseudogobius olorum*	✓	
Total number of *Pseudogobius olorum*	✓	

1.3. Evaluation of the Fish Community Indices

The Fish Community Indices produced by Hallett (2010) for the Swan-Canning Estuary, and the process of their development, may be evaluated against the key requirements of effective indicators (Table 2) that have been identified by Niemeijer and de Groot (2008) and M. Robb (DoW, personal communication).

Table 2. Evaluation of the nearshore and offshore Fish Community Indices developed for the Swan-Canning Estuary (see Hallett 2010, Hallett et al. 2012b for more details). Outstanding issues have been italicised.

Criterion	***Evaluation***	
Objective	✓	The indices were developed, and designed to be implemented, using objective procedures with a minimal input of subjective judgement.
Rigorous	✓	The rationale behind the indices has been clearly defined and they are conceptually well understood (see Fig. 1). They are measurable in both quantitative (scores of 0-100) and qualitative (condition category) terms. Index development has employed widely accepted approaches, assumptions and techniques. Where novel methodologies were required, these were developed and applied with

Criterion		*Evaluation*
		a focus on statistical rigour and subjected to scientific peer-review (*e.g.* Hallett et al. 2012b).
Robust	✓	Various steps to minimise the influence of 'noise' (replicate to replicate variability) and natural or sampling differences were taken throughout index development. This included eliminating erratically variable metrics, accounting for natural spatial and temporal influences on fish metric values, and standardising the data for methodological biases. This ensures that the resulting indices are able to detect the effects of anthropogenic changes against a background of natural and/or sampling-related variability. Preliminary validation of the indices has shown that that provisional classification of the condition status of the estuary was fairly robust and reliable (most notably in the case of the nearshore index) when the above effects were accounted for.
Repeatable	✓	The indices were designed to be straightforward, repeatable and inexpensive to measure, analyse and interpret, requiring expert input only for the correct identification of captured fish species. Repeatability of the index has been ensured by the development of a clear set of standard protocols, which are easily understood by any person with general scientific knowledge. More broadly, the approach and techniques for developing these indices could easily be modified for application to other estuaries across the south-west bioregion.
Sensitive	?	The consistent decrease observed in offshore index scores over the last three decades strongly suggests that this index is capable of detecting the widely-perceived, long-term decline in the condition of the offshore waters of the Swan-Canning Estuary. *However, the sensitivity of these indices to specific human-caused stressors over smaller spatial and temporal scales has not been demonstrated to date.*
Consistent	?	Preliminary validation has demonstrated that provisional estuarine condition status classifications were not unduly affected by random sampling variability or by natural, inter-seasonal variability in the case of the nearshore index. *However, the consistency of index scores between repeated sampling occasions within the same season has yet to be determined for either index. Also, and especially given the potentially higher incidence of zero catches in the case of the gill net samples from which the offshore index scores are derived, it is essential that the effect of spatial sampling intensity on the consistency of index scores is established.*
Communicable	✓	Index outputs can be communicated quantitatively and qualitatively (*e.g.* good, fair, poor, very poor or as alphanumeric grades A-D) and are simply and easily understood by managers and the public alike. Index scores may be calculated for the system as a whole on an annual basis, or for individual ecological management zones and/or seasons.

These indices clearly possess several advantages over simple water quality measures as a tool for estuarine condition reporting, but several questions remain regarding their capacity for future implementation. Previous validation of the nearshore and offshore condition indices has demonstrated their broad capability for tracking long-term changes in the perceived condition of the Swan-Canning Estuary, and of its constituent zones (Hallett 2010; Valesini et al. 2011). However, as detailed in Table 2, their sensitivity to specific stressors affecting this estuary remains unquantified. In addition, the appropriate sampling intensity for a future monitoring regime needs to be determined to ensure that the indices provide a reliable tool for future ecological assessment of the Swan-Canning Riverpark. The current study was funded by the SRT and Murdoch University to address these issues (Fig. 3).

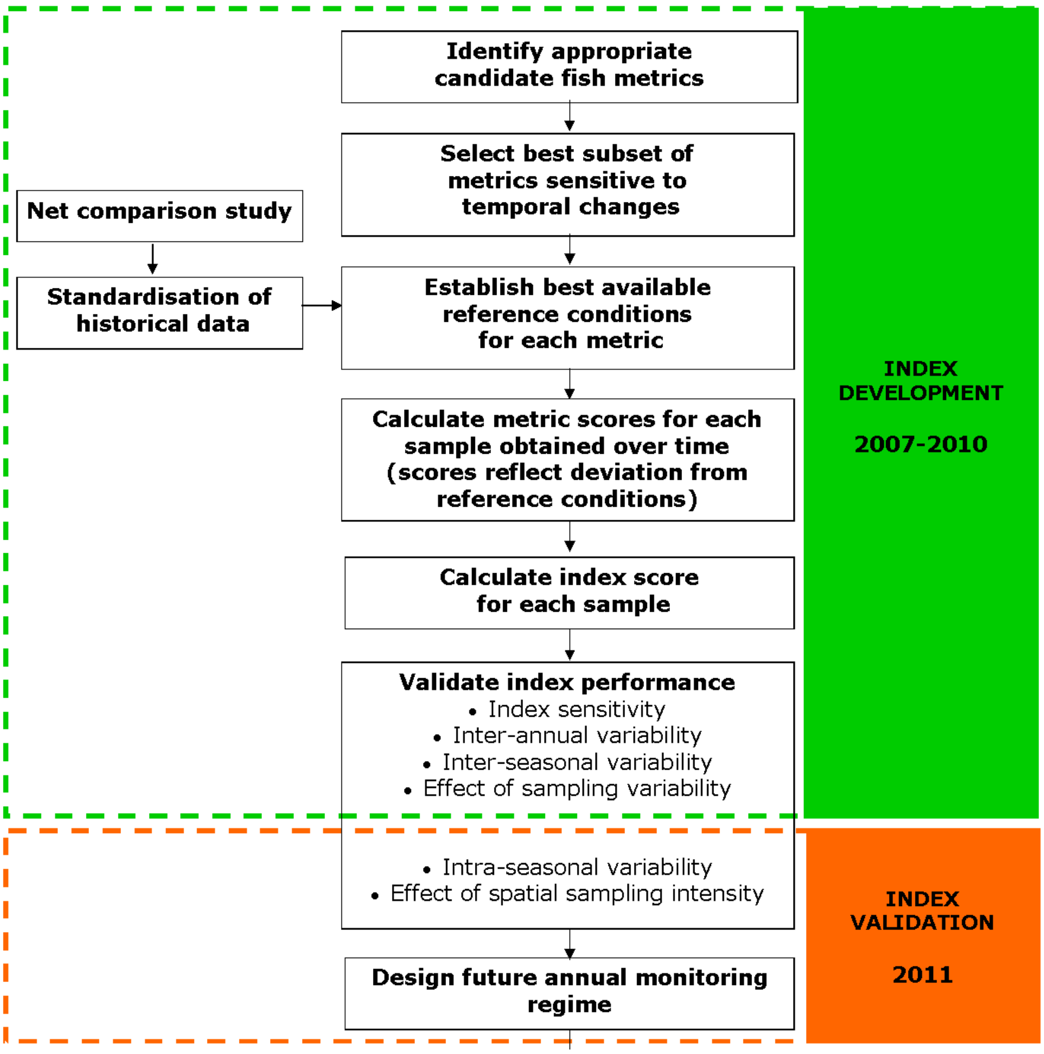


Figure 3. Summary of the stages in the development and validation of multimetric Fish Community Indices for the Swan-Canning Estuary

1.4. Review of the Fish Community Index condition grading system

Previous studies have proposed a straightforward system for determining estuarine condition grades based on index scores. This approach, which subdivided the possible range of index scores arbitrarily into four classes of equal breadth to provide qualitative descriptions (*i.e.* good, fair, poor, very poor; Hallett 2010, Valesini et al. 2011), was considered to be potentially skewed toward producing fair to good grades. Consequently, in July 2012 the SRT provided additional funding to conduct a comparative evaluation and review of alternative systems for determining estuarine condition grades/categories. This review is intended to provide greater confidence in the outputs of the indices and ensure that they are consistent with the needs of proposed Riverpark report cards.

1.5. Objectives of the current study

1. **Determine the sampling intensity required** for any future monitoring regime, via appropriate power analyses.
2. **Examine intra-seasonal variability** of the condition indices by comparing monthly index scores for sites sampled repeatedly within the same season. This will enable a determination of the optimum timing and length of the sampling period required for any future monitoring regime.
3. **Demonstrate the sensitivity of the condition indices** to short-term, spatially discrete environmental perturbations (*e.g.* algal blooms) which might occur during the course of the study.
4. **Review the current, provisional system for determining condition grades** and evaluate a range of alternative grading systems.
5. In light of the findings from objectives 1-4, **design a monitoring regime and sampling and analytical protocols** to enable the condition of the Swan-Canning Estuary to be quantified reliably into the future using these Fish Community Indices.

This report is structured to reflect these aims. Sections 2 and 3 detail the activities and analyses carried out to validate the sensitivity of the indices, based on the provisional condition classification system developed during previous work (Hallett 2010, Valesini et al. 2011). Section 4 provides a detailed review and comparative evaluation of alternative systems for determining condition grades. Finally, section 5 draws together the findings of the preceding analyses and outlines the design of a monitoring regime which will allow the index to be implemented as a tool for measuring and communicating estuarine condition.

2. Index validation - Methodology

2.1. Sampling of fish assemblages

Sampling of the nearshore and offshore fish assemblages was performed once in each of the middle and final months of both summer and autumn 2011, at each of the sites illustrated in Fig. 4. Sampling was restricted to summer and autumn as the diversity of fish assemblages was previously shown to be highest and most stable during these seasons, and they thus represent the optimum window for index implementation (Hallett 2010).

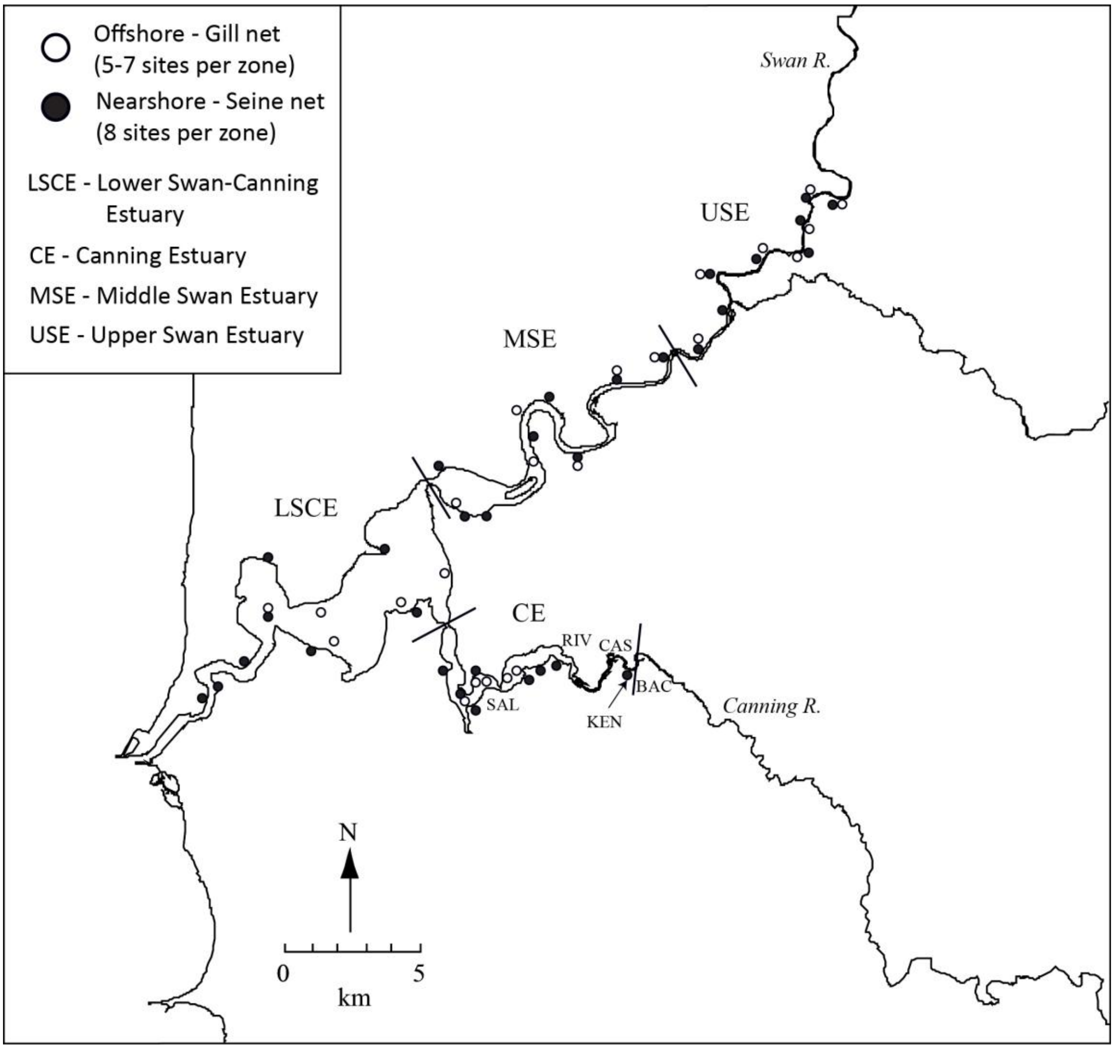


Figure 4. Map of the Swan-Canning Estuary, showing the locations of the nearshore (<2 m depth) and offshore (>2 m depth) sites at which fish assemblages were sampled during the current study, and the management zones of this system. Labels highlight locations referred to in the text.

The fish assemblages at each nearshore site were sampled using a seine net that was 21.5 m long, 1.5 m deep and comprised two 10 m-long wings (6 m of 9 mm mesh and 4 m of 3 mm mesh) and a 1.5 m-long bunt (3 mm mesh). This net type has previously been identified as the optimum method for sampling nearshore fish communities in the Swan-Canning Estuary, due to the ease with which it can be deployed across several habitats and its lower impact on fish populations in comparison to larger counterparts (Hallett 2010). The net, which was laid parallel to the shore and then hauled onto the beach, swept an area of *ca.* 116 m^2. Fish at the offshore sites were sampled using sunken, multimesh gill nets that consisted of eight 20 m-long panels with stretched mesh sizes of 35, 51, 63, 76, 89, 102, 115 and 127 mm. These nets were deployed at sunset and retrieved after three hours, consistent with the methodology employed during previous studies.

Following regular sampling carried out in late April and early May 2011, the SRT reported that an algal bloom (comprising the potential fish-killing dinoflagellate *Karlodinium veneficum*) was affecting upstream areas of the Canning Estuary and the Lower Canning River. In response, the above nearshore sampling regime was supplemented by additional sampling of nearshore fish assemblages at particular sites throughout the Canning Estuary (CE) zone during May 2011. As algal blooms are one of the leading stressors impacting the Swan-Canning Estuary (SRT 2009), this bloom event provided an opportunity to test the sensitivity of the nearshore index to a small-scale environmental perturbation. Fish assemblages at the five uppermost nearshore sites in the CE zone were thus resampled on the 16th and 27th May, representing 'mid-bloom' and 'post-bloom' conditions respectively, both of which could be compared to the 'pre-bloom' conditions of prior sampling occasions (13th April to the 11th May).

All fish collected were immediately placed in an ice slurry and taken to the laboratory for processing, except where large numbers (*e.g.* thousands) of fish were caught, in which case a subsample of the catch (*e.g.* half to one-eighth) was retained and the remainder returned alive to their environment. All fish were identified to species and the total numbers of individuals belonging to each species in each sample were recorded. In those cases in which the catch was subsampled, the number of fish of each species in the original sample was calculated by extrapolation from the number in the subsample.

Water quality data were collected concurrently with sampling of the fish community. At each nearshore site on each sampling occasion, water temperature (˚C), salinity and dissolved oxygen concentration (mg/L) were measured in the middle of the water column using a Yellow Springs Instrument 556 MPS water quality meter. The same instrument was also used to measure these variables from the surface and bottom of the water column at each offshore site on each sampling occasion.

2.2. Calculation of metric and index scores

The species abundance data from each sample were used to derive values for each of the relevant metrics comprising the nearshore and offshore Fish Community Indices (Table 1). Metric scores were then calculated from these metric values, which were in turn combined to form the index scores. The detailed methodology for how this is achieved is provided in section 5.2, but can be simply summarised as follows.

1. Calculate metric values for each sample, after allocating each of its component fish species to their appropriate Habitat guild, Estuarine Use guild and Feeding Mode guild.
2. Convert metric values to metric scores (0-10) via comparison with the appropriate (zone- and season-specific) reference condition values for each metric.
3. Combine scores for the component metrics into an index score (0-100) for each sample.
4. Compare the index score to scoring thresholds to determine the (provisional) qualitative condition status for the sample (*i.e.* good ≥ 75; fair ≥ 50 < 75; poor ≥ 25 < 50; very poor < 25).

2.3. Determination of appropriate spatial sampling intensity

For both the nearshore and offshore waters in each zone, the index scores calculated from the samples collected in summer and autumn were used in power analyses to determine the Minimum Detectable Effect Size (MDES; *i.e.* the change in mean index score of a zone from one sampling occasion to another) that could be detected with 95% confidence for sample sizes (n) of two to eight sites per zone. Given the scale and additive nature of the index scores, the Central Limit Theorem suggests that index scores can generally be assumed to approximate a normal distribution (K. Pollock, Murdoch University, personal communication). Power analyses were therefore conducted on the basis of two-sample, unpaired t-tests with common variance, using freely available web software (Lenth 2009). The power for each test was set by convention at 0.8 and the significance level (α) at 0.05 (Quinn and Keough 2002). The average standard deviation of scores obtained in a zone across the four sampling months was used as the estimate of the standard deviation in power analyses for that zone. Similar power analyses were also performed at the estuary level for both the nearshore and offshore indices.

2.4. Intra-seasonal variability of index scores

Month to month changes in the nearshore and offshore index scores for each individual site were quantified in each season, and the resultant changes in qualitative condition status examined. Intra-seasonal changes in mean nearshore and offshore scores across each zone, and across the estuary as a whole, were also similarly assessed.

Boxplots were then used to examine month to month changes in the statistical distribution of all nearshore and offshore index scores in both seasons. Although the distribution of all scores observed across the four months approximated a normal distribution, the index scores from any individual month were not normally distributed. Therefore, non-parametric Mann-Whitney-Wilcoxon rank sum tests (with Bonferroni corrections for repeated tests) were used to ascertain whether the distributions of index scores in each month differed significantly.

2.5. Index sensitivity to algal blooms

2.5.1. Karlodinium veneficum *bloom of May 2011*

An algal bloom that occurred in the Canning Estuary (CE) zone (Fig. 5) during May 2011 provided an opportunity to assess the sensitivity of the nearshore index to a short-term, spatially discrete environmental perturbation. On the 10th May, the fish-killing dinoflagellate *Karlodinium veneficum* was noted at elevated densities at Riverton Bridge (4,290 cells/mL) and Bacon St (1,263 cells/mL), and exceeded the SRT's management trigger level for this species (10,000 cells/mL) at Castledare, where densities peaked in excess of 30,000 cells/mL (SRT, unpublished data). By May 17th, the densities of *K. veneficum* at Castledare and Riverton Bridge had decreased, whilst sites at or upstream of Kent St Weir were exhibiting increased densities. By May 24th, the bloom had collapsed and cell densities had decreased dramatically at all of the above sites due to the influence of rainfall and freshwater flow.

Nearshore fish assemblages in the CE zone had previously been sampled from sites downstream of Riverton Bridge (Fig. 5) immediately prior to the bloom, during the course of the routine monthly sampling described in section 2.1. These sites were resampled on May 16th, in the middle of the bloom period, and on May 27th, following the end of the bloom. Nearshore index scores were calculated for each of these samples, as detailed in section 2.2, and nearshore index sensitivity was then assessed by comparing the index scores for samples collected during the bloom ('mid-bloom') to those which had been collected 'pre-bloom' (*i.e.* during April and/or early May) and to those collected after the bloom had collapsed ('post bloom').

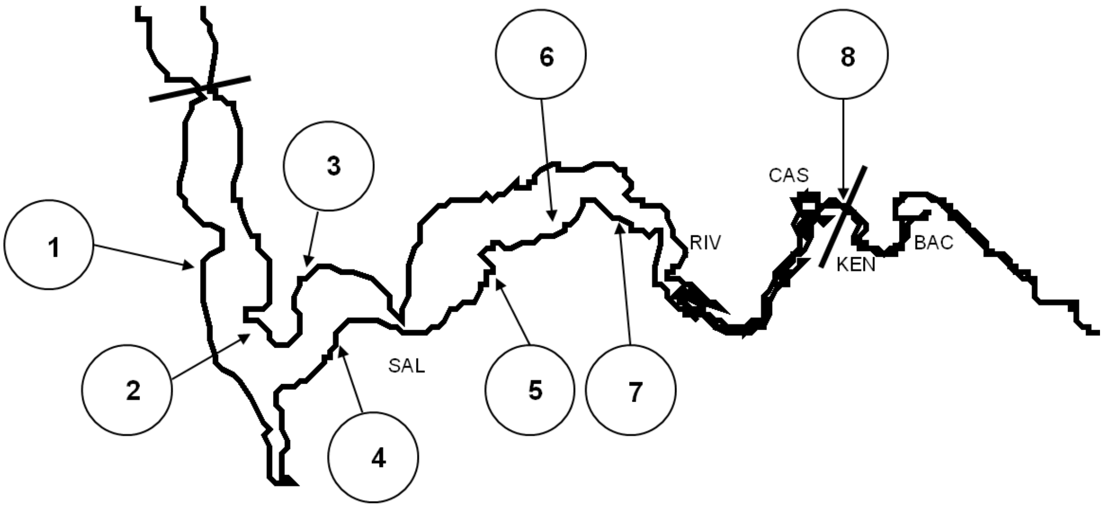


Figure 5. Map of the Canning Estuary zone of the Swan-Canning Estuary, illustrating nearshore fish sampling sites (circled) and locations referred to in the text; SAL – Salter Point, RIV – Riverton Bridge, CAS – Castledare, KEN – Kent St Weir, BAC – Bacon Street.

2.5.2. Karlodinium veneficum *bloom of March 2004*

Given that the May 2011 bloom occurred over a relatively small spatial and temporal scale, and that offshore index responses to the above bloom could not be validated (see section 3.3.1), we also sought to assess nearshore and offshore index responses to a broader scale algal bloom event that had occurred historically in the Swan-Canning Estuary. A study of the nearshore and offshore fish communities in this system during 2003-04, carried out by researchers from Murdoch University (Valesini et al. 2005, unpublished report), coincided with the occurrence of a significant algal bloom in the Swan River during March 2004. A large bloom of *K. veneficum* occurred in the middle-upstream (MU) region of the Swan River during early to mid-March 2004 (Fig. 6). Cell densities of this species increased above 20,000 cells/mL in the last week of February 2004 and continued to rise until mid-March, where they peaked at *ca* 94,000 cells/mL (Valesini et al. 2005). In the course of the study, fish assemblages were sampled at a range of nearshore and offshore sites throughout the Lower Swan River (LS) to Upper Swan River (US) regions (Fig. 6). Samples were collected in mid-summer (*ca* six weeks prior to the bloom), during the peak of the bloom period and *ca* three weeks after the peak of the bloom (*i.e.* in mid-autumn). Offshore sites were sampled using multimesh gill nets as described in section 2.1, whereas the nearshore sites were sampled using a seine net that was 41.5 m long, 2 m deep and consisted of two 20 m long wings made of 25 mm mesh and a 1.5 m wide central bunt made of 9 mm mesh. This net, which swept an area of 274 m^2, was laid in a semi-circle from the bank by boat and then hauled on to the beach (Valesini et al. 2005). Accompanying measurements of water quality parameters, and the processing of fish samples, were performed as outlined in section 2.1, and index scores calculated for these samples as described in section 2.2.

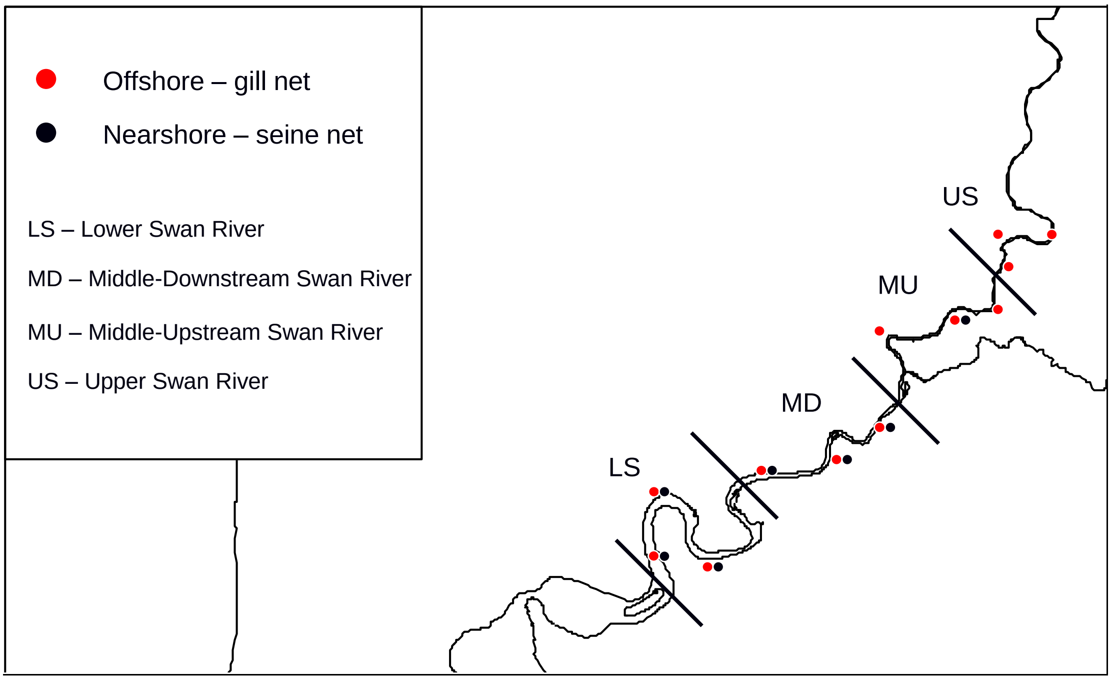


Figure 6. Map of the Swan River (Middle Swan Estuary and Upper Swan Estuary management zones), illustrating the nearshore and offshore sites at which fish assemblages were sampled during the study of 2003-04, and the finer-scale regions into which the river was previously divided.

3. Index validation - Results and discussion

3.1. Determination of appropriate spatial sampling intensity

Power analyses conducted for the nearshore index demonstrated that an increase in the spatial intensity of sampling from two to four sites dramatically decreases the MDES in each zone at $\alpha = 0.05$ (Fig. 7). Thus, for example, if only two sites were sampled within the USE zone on two different occasions, a difference in mean index score of *ca* 50 points would have to be observed in order to conclude with 95% probability that a statistically significant change in ecosystem condition had occurred between sampling events. In contrast, a difference of just 20 points would constitute a statistically significant change if four sites were sampled per zone. Whilst the curve for the USE zone is uppermost (reflecting the generally greater variability of the nearshore scores observed within this zone), the curves for all zones followed a similar and typical pattern of declining returns on increasing investment in sample size. Thus, beyond *ca* six samples per zone (*i.e.* the point at which the curves begin to flatten), further increases in sampling intensity will generate comparatively small gains in detectable effect size (Fig. 7). On the basis of these results, it is recommended that any future sampling regime for the nearshore index should employ a minimum sampling intensity of six sites per zone, although it should be noted that a further two nearshore sites per zone could be sampled at little additional cost.

A nearshore sampling intensity of ≥ 6 sites per zone, when applied across all four zones of the estuary, would generate a MDES for the system as a whole of 8.5 index points (Fig. 8) and is considered to provide an adequate level of replication for detecting significant changes in the ecological condition of the nearshore waters of the Swan-Canning Riverpark as a whole.

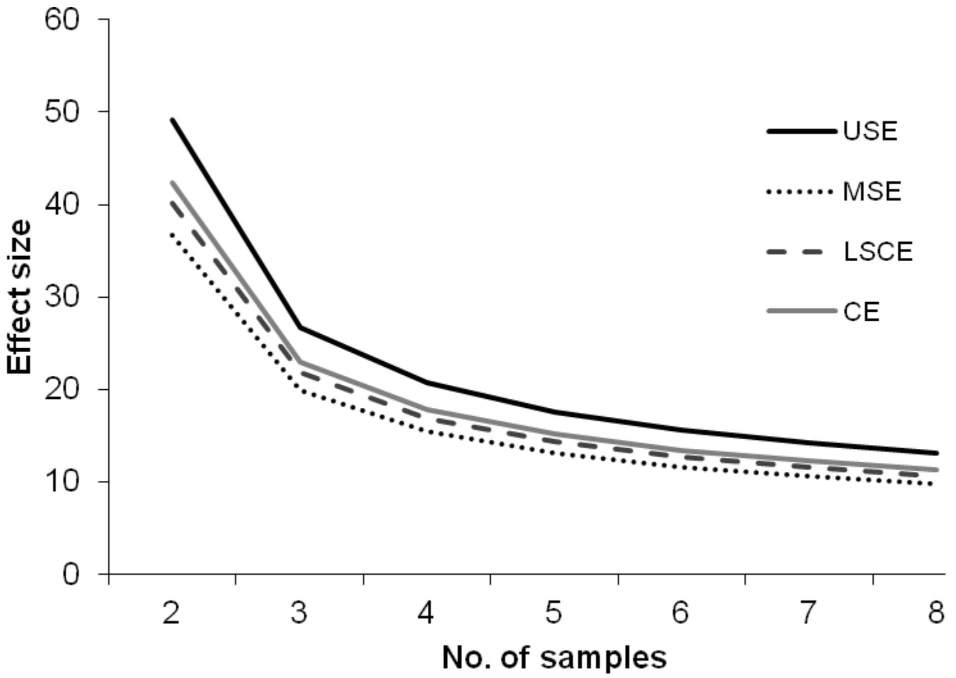


Figure 7. Curves of minimum detectable effect sizes (*i.e.* change in index score) for the nearshore index (at α = 0.05) as a function of increasing sampling intensity in each zone of the Swan-Canning Estuary.

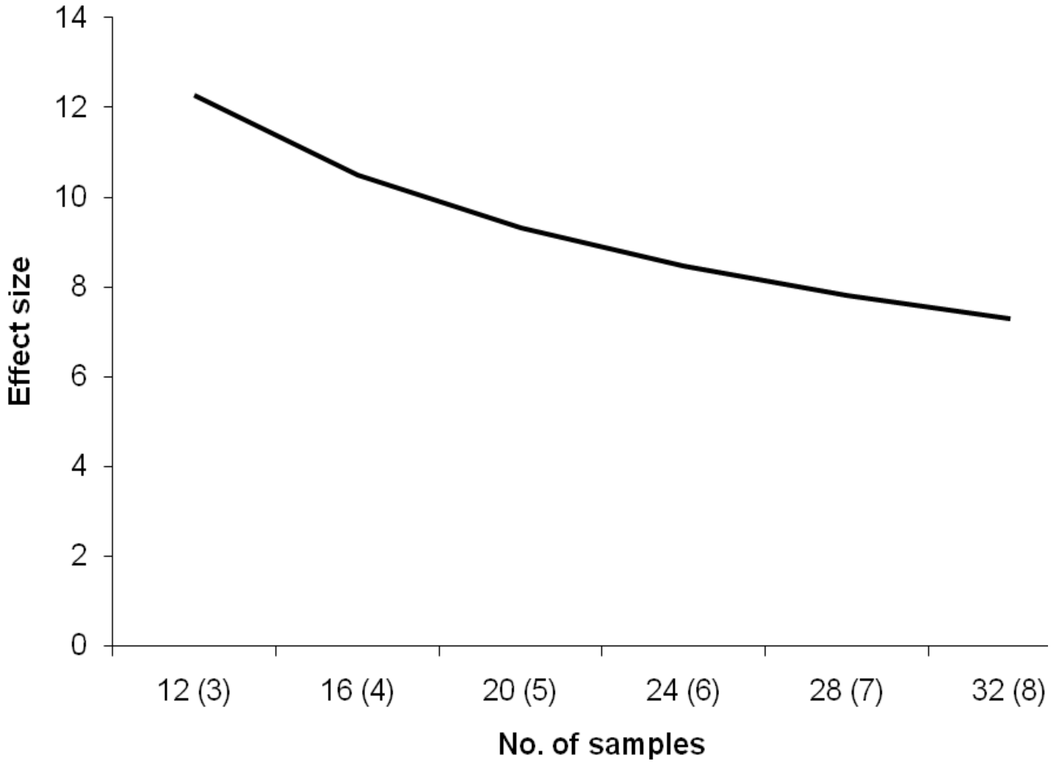


Figure 8. Curve of minimum detectable effect size (*i.e.* change in index score) for the nearshore index (at α = 0.05) as a function of increasing sampling intensity across the entire estuary. (Numbers in parentheses present sampling intensities on a per zone basis).

The observed variability of offshore scores was broadly similar to that of the nearshore index. Thus, increasing the spatial intensity of offshore sampling from two to four sites per zone again dramatically decreases the MDES at α = 0.05 (Fig. 9), whereas further increasing the number of samples beyond five or six per zone returns only small gains in detectable effect size. These results indicate that a sampling intensity of six sites per zone provides the most cost-effective yet statistically robust sampling regime for future implementation of the offshore index. It should also be noted that significant cost increases would be associated with offshore sampling intensities of more than six sites per zone, as only three replicate gill nets can safely and effectively be set each night.

A sampling intensity of 6 offshore sites per zone again equates to a MDES of around 8.5 index points for the Swan-Canning Estuary as a whole (Fig. 10), and would thus provide an adequate level of replication for detecting significant changes in the ecological condition of the deeper waters throughout the system.

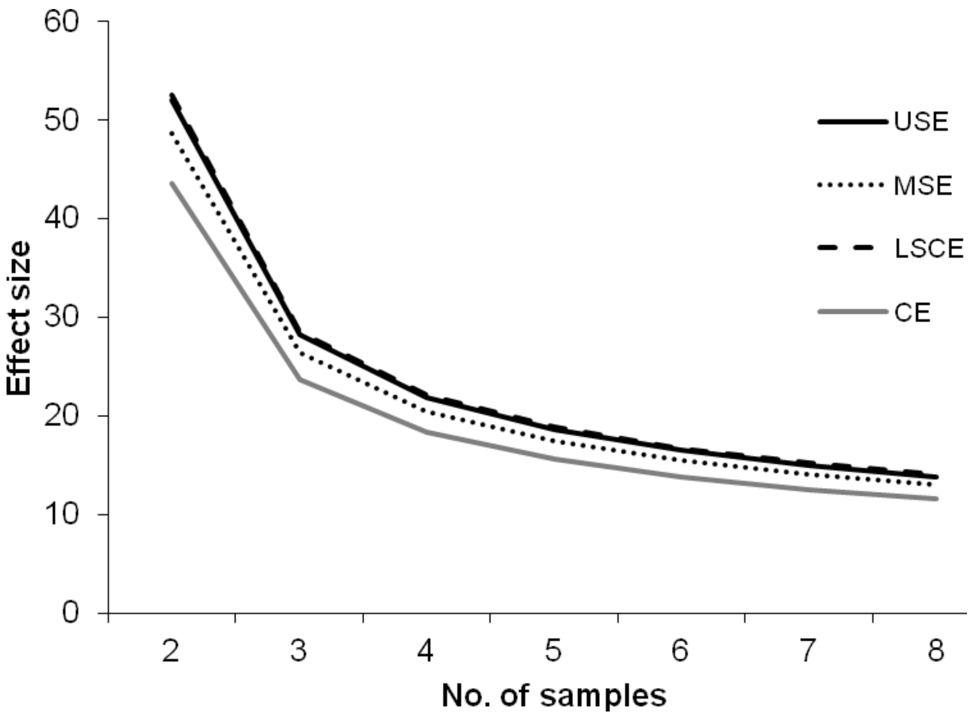


Figure 9. Curves of minimum detectable effect sizes (*i.e.* change in index score) for the offshore index (at α = 0.05) as a function of increasing sampling intensity in each zone of the Swan-Canning Estuary.

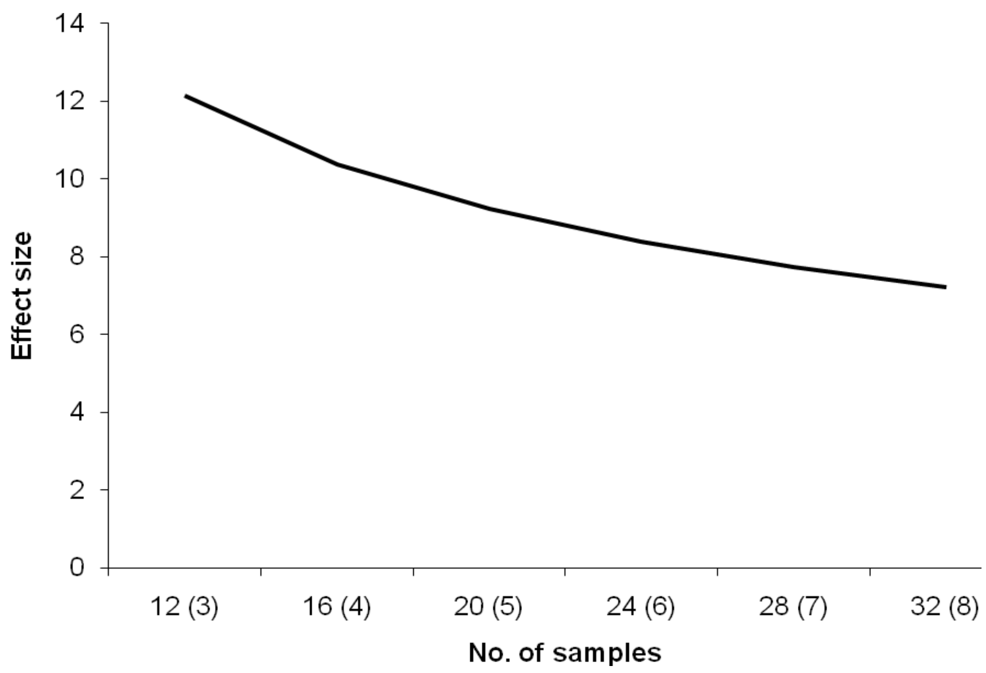


Figure 10. Curve of minimum detectable effect size (*i.e.* change in index score) for the offshore index (at α = 0.05) as a function of increasing sampling intensity across the entire estuary. (Numbers in parentheses present sampling intensities on a per zone basis.)

3.2. Intra-seasonal variability of index scores

Considerable changes in nearshore index scores were observed from month-to-month (*i.e.* within a season) at some sites. During summer, these changes ranged from 0.7 to 26.6 (with a mean of 8.4) for any individual site and led to a change in the condition classification of ten of the 32 nearshore sites surveyed. In autumn, nearshore index scores for any individual site similarly varied by 0.5 – 25.4 points between months, with a mean of 6.5, resulting in a change in condition status for seven of the 32 sites.

Although the extents of intra-seasonal changes in nearshore index scores were thus considerable at the site-level in both seasons, they were far less pronounced at the broader scale of estuarine zones, *i.e.* the spatial scale at which the indices are intended to be used. The month-to-month change in mean nearshore index score for any zone ranged from 0.8 to 7.1 (mean = 3.7) points in summer, and from 3.0 to 6.9 (mean = 4.2) in autumn (Table 3). Moreover, this level of variability did not result in a change in the nearshore condition status of any zone in either season, based on the provisional grading system. On a yet broader scale, the mean nearshore index score across the whole estuary changed from 64.4 to 64.1 between January and February and from 65.4 in April to 63.0 in May, with the condition of the estuary being classified, provisionally, as fair throughout all four months.

Table 3. Mean (± SE) nearshore index scores across sites sampled during the middle months (month 1) and final months (month 2) of summer and autumn 2011 in each zone of the Swan-Canning Estuary, and across the entire estuary. Numbers in parentheses represent the numbers of sites sampled.

	Summer		**Autumn**	
Zone	Month 1	Month 2	Month 1	Month 2
LSCE (*n* = 8)	70.0 ± 6.6	63.0 ± 3.8	64.8 ± 2.1	61.7 ± 2.3
CE (*n* = 8)	59.8 ± 3.2	61.7 ± 3.9	71.5 ± 1.4	68.5 ± 2.9
MSE (*n* = 8)	60.2 ± 3.3	59.4 ± 2.6	62.7 ± 2.6	66.3 ± 1.3
USE (*n* = 8)	67.5 ± 3.9	72.5 ± 2.3	62.5 ± 3.4	55.6 ± 3.6
Estuary (*n* = 32)	**64.4 ± 1.7**	**64.1 ± 1.7**	**65.4 ± 1.3**	**63.0 ± 1.5**

Considerable changes from month to month were also observed in offshore index scores at some sites. The intra-seasonal change in index score for any individual offshore site ranged from 1.9 to 28.9 in summer, with a mean of 10.4 (Table 4). In autumn, offshore index scores for any individual site varied by as much as 32.8 points between months (mean = 11.4). This variability led to a change in the provisional condition status of ten of the 23 offshore sites, in both seasons.

Table 4. Mean (± SE) offshore index scores across sites sampled during the middle months (month 1) and final months (month 2) of summer and autumn 2011 in each zone of the Swan-Canning Estuary, and across the entire estuary. Numbers in parentheses represent the numbers of sites sampled.

	Summer		**Autumn**	
Zone	Month 1	Month 2	Month 1	Month 2
LSCE (*n* = 5)	60.7 ± 5.9	68.7 ± 3.7	60.9 ± 3.5	55.8 ± 5.5
CE (*n* = 5)	57.3 ± 3.5	50.3 ± 4.4	56.2 ± 2.2	53.7 ± 5.4
MSE (*n* = 6)	67.9 ± 3.5	63.5 ± 3.0	51.2 ± 3.3	57.9 ± 5.7
USE (*n* = 7)	65.1 ± 5.0	63.0 ± 2.6	61.0 ± 2.1	51.3 ± 5.4
Estuary (*n* = 23)	**63.2 ± 2.2**	**61.6 ± 2.0**	**57.4 ± 1.5**	**54.5 ± 2.5**

Again, however, intra-seasonal changes in mean offshore scores were less pronounced at the broader, zonal scale. The month-to-month change in mean offshore index score for any zone ranged from 2.1 to 7.9 (mean = 5.4) in summer, and from 2.5 to 9.7 (mean = 6.0) in autumn (Table 4). Again, this variation did not result in a change in the offshore condition status of any zone in either season, under the provisional grading system. Similarly, the offshore condition of the whole estuary was classified provisionally as fair throughout all four months, with the mean offshore index score for the whole estuary changing from 63.2 in January to 61.6 in February, and from 57.4 to 54.5 between April and May.

The following boxplots also demonstrate that the distribution of nearshore index scores across the whole estuary (including those from supplementary sampling around the May 2011 bloom) was broadly similar from month to month in both seasons (Fig. 11). These box plots present median scores as dark horizontal bars and the first and third quartiles of the data as upper and lower bounds of the boxes, respectively. Dashed whiskers illustrate either the maximum observed values or *ca* two standard deviations (whichever is the smaller value), and any remaining outliers are plotted individually.

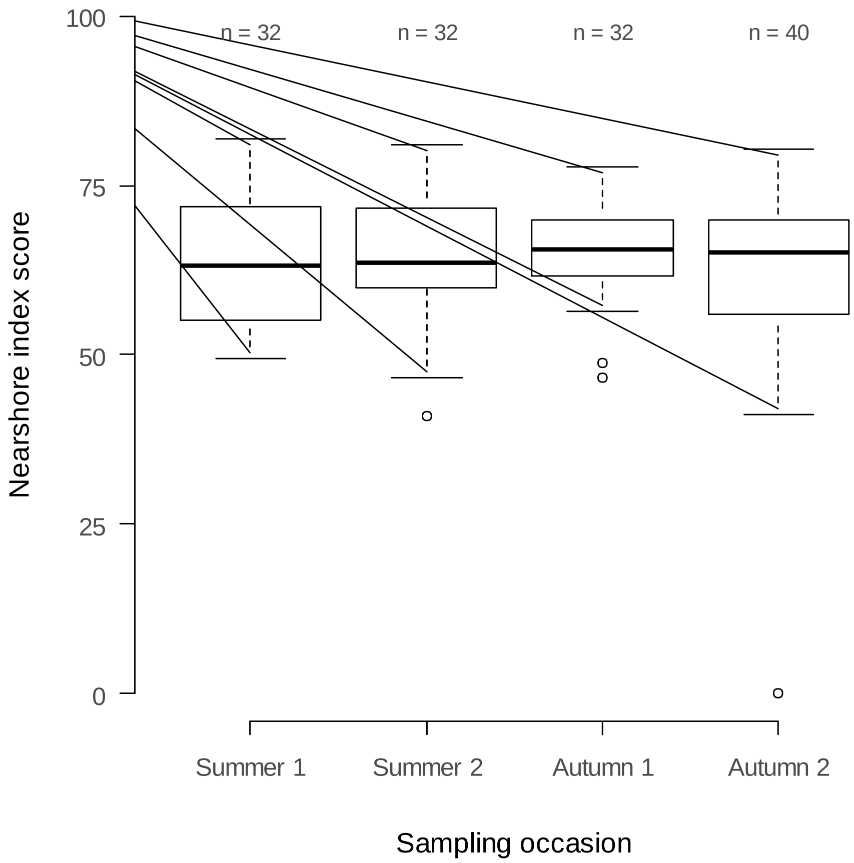


Figure 11. The distributions of nearshore index scores obtained during each month of sampling in summer and autumn 2011. Sample sizes (n) for each month are shown above boxplots.

Median nearshore index scores observed across all sites from the first and second sampling occasions during summer were 63.1 and 63.6, respectively. The distributions of scores in the two summer months did not differ significantly (Mann-Whitney-Wilcoxon W = 508, $n_1 = n_2$ = 32, p = 0.963). Similarly, the distributions of nearshore index scores from the first (median = 65.6) and second (median = 65.1) sampling occasions during autumn were not significantly different (W = 719, n_1 = 32, n_2 = 40, p = 0.376). Moreover, the distribution of nearshore index scores did not differ significantly between seasons (W = 2314, n_1 = 64, n_2 = 72, p = 0.967).

Median offshore index scores observed across all sites from the first and second sampling occasions during summer were 64.1 and 61.7, respectively. The distributions of scores in the two summer months did not differ significantly (W = 283, $n_1 = n_2$ = 23, p = 0.695). Similarly, the distributions of nearshore index scores from the first (median = 56.9) and second (median = 55.8) sampling occasions during autumn did not differ significantly (W = 311, $n_1 = n_2$ = 23, p = 0.315). However, the distribution of offshore index scores across all samples collected during summer (median = 62.3) differed significantly from that across all autumn samples (median = 56.1; W = 669, $n_1 = n_2$ = 46, p = 0.002), in that lower median scores were observed during autumn (Fig. 12).

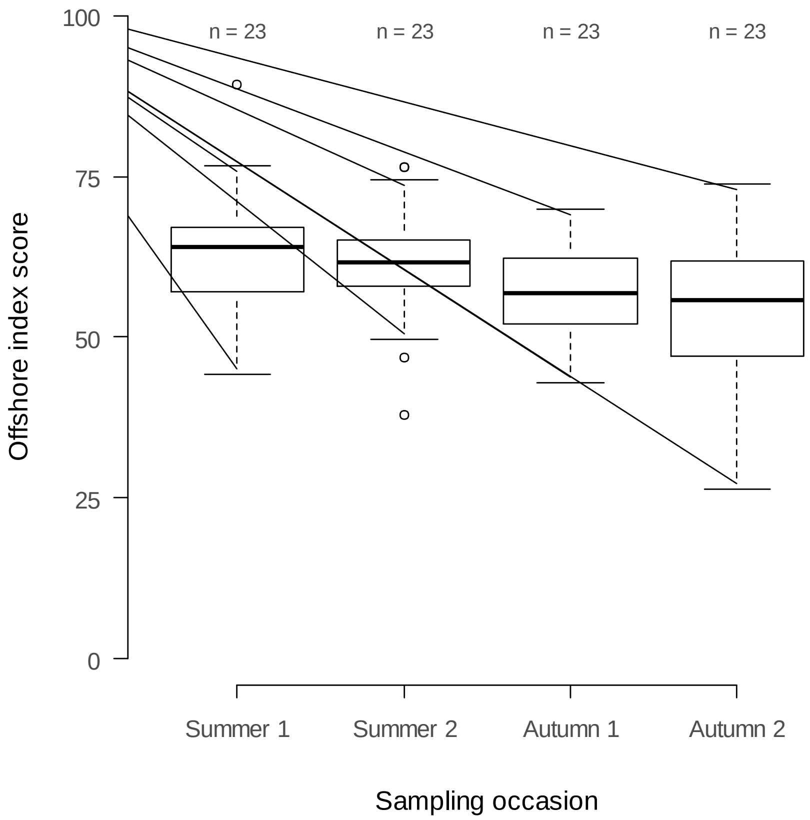


Figure 12. The distributions of offshore index scores obtained during each month of sampling in summer and autumn 2011. Sample sizes (n) for each month are shown above boxplots.

The above results indicate that the nearshore and offshore indices are robust to the effects of natural, intra-seasonal variability in environmental conditions, and thus provide reliable tools for quantifying and classifying the ecological condition of the Swan-Canning Estuary and its constituent management zones. Moreover, they demonstrate that repeated sampling across multiple months within a season is not necessary to adequately capture the provisional condition status of the estuary, or of a particular zone, in that season. However, given that summer and autumn have previously been identified as the optimum period in which to implement the index, and that the condition of the estuary may change between seasons (*e.g.* in response to the occurrence of algal blooms in one or more seasons), it is recommended that any future monitoring regime should include both summer and autumn sampling and consider additional sampling around algal blooms (see section 5.2).

3.3. Index sensitivity to algal blooms

3.3.1. Karlodinium veneficum *bloom of May 2011*

Nearshore index scores for samples collected in the CE during late April 2011 indicated that the provisional condition of this zone was fair to good (mean score of 71.5), with most sites exhibiting scores of between 66 and 72 (fair) and two sites with scores of 76.8 (good; Fig. 13a). As of May 11th, the provisional condition of this zone had changed little since the previous sampling occasion (*i.e.* a drop of only 0.5 points in the mean score), with individual site scores ranging between 62 and 73 (fair) and one site being provisionally categorized as good (Fig. 13b). This finding again confirms that the nearshore Fish Community Index is robust (*i.e.* it is not overly sensitive to natural, background variability).

At the mid-point of the bloom, however, the scores for each nearshore site had decreased by between two and 29 points. As of May 16th, the ecological condition of sites located between Salter Point and Kent St Weir had been considerably impacted and, although the overall condition of the CE was still assessed as fair at this time, the mean score for the zone had decreased by more than 10 points to 60.8 (Fig. 13c). Most notably, a mid-bloom sample collected from a site immediately downstream of Kent St Weir returned only two fish, with a corresponding score of 42.7 (poor).

Following the collapse of the bloom, the provisional condition of the CE zone subsequently recovered towards its pre-bloom status, with the mean score for the zone reaching 68.1 by the time of the post-bloom sampling (Fig. 13d). Nearshore scores for each individual site had rebounded by two to 16 points between May 16th and 27th, by which time all sites were provisionally categorized as being in fair condition.

Together, these findings suggest that the nearshore index is sufficiently sensitive to quantify ecological condition responses to local-scale environmental perturbations such as algal blooms, and also to track the subsequent recovery of the system following their removal. Nearshore index scores at sites within the area affected by the algal bloom exhibited a clear decrease from pre-bloom conditions. In the absence of any observed fish kill, it is argued that this reflects the movement of fish away from these affected areas to escape the general decline in habitat (*i.e.* water) quality which would accompany such a bloom. As the bloom senesced and collapsed, and environmental conditions returned to pre-bloom levels, the diverse fish fauna that typify a healthy CE zone are thought to have recolonised previously bloom-affected areas, thus generating the consequent recovery of index scores.

It is unfortunate that similar analyses could not be performed to validate the sensitivity of the offshore index to this algal bloom event. Although sampling of the offshore sites in the CE had been completed in early May, prior to the onset of the bloom, it was not possible to resample these offshore sites during and/or after the bloom due to the need to complete the routine monthly sampling of offshore sites in the other management zones as a priority in the limited time available.

Moreover, technical issues experienced with water quality monitoring equipment at this time prevented the examination of accompanying trends in water quality variables over the bloom period. No correlations between Fish Community Index scores and ambient water quality conditions could thus be identified. However, it is unlikely that such a correlation between index scores and any individual water quality variable would have been identified, for reasons detailed in the following consideration of an historical algal bloom in the tidal reaches of the Swan River.

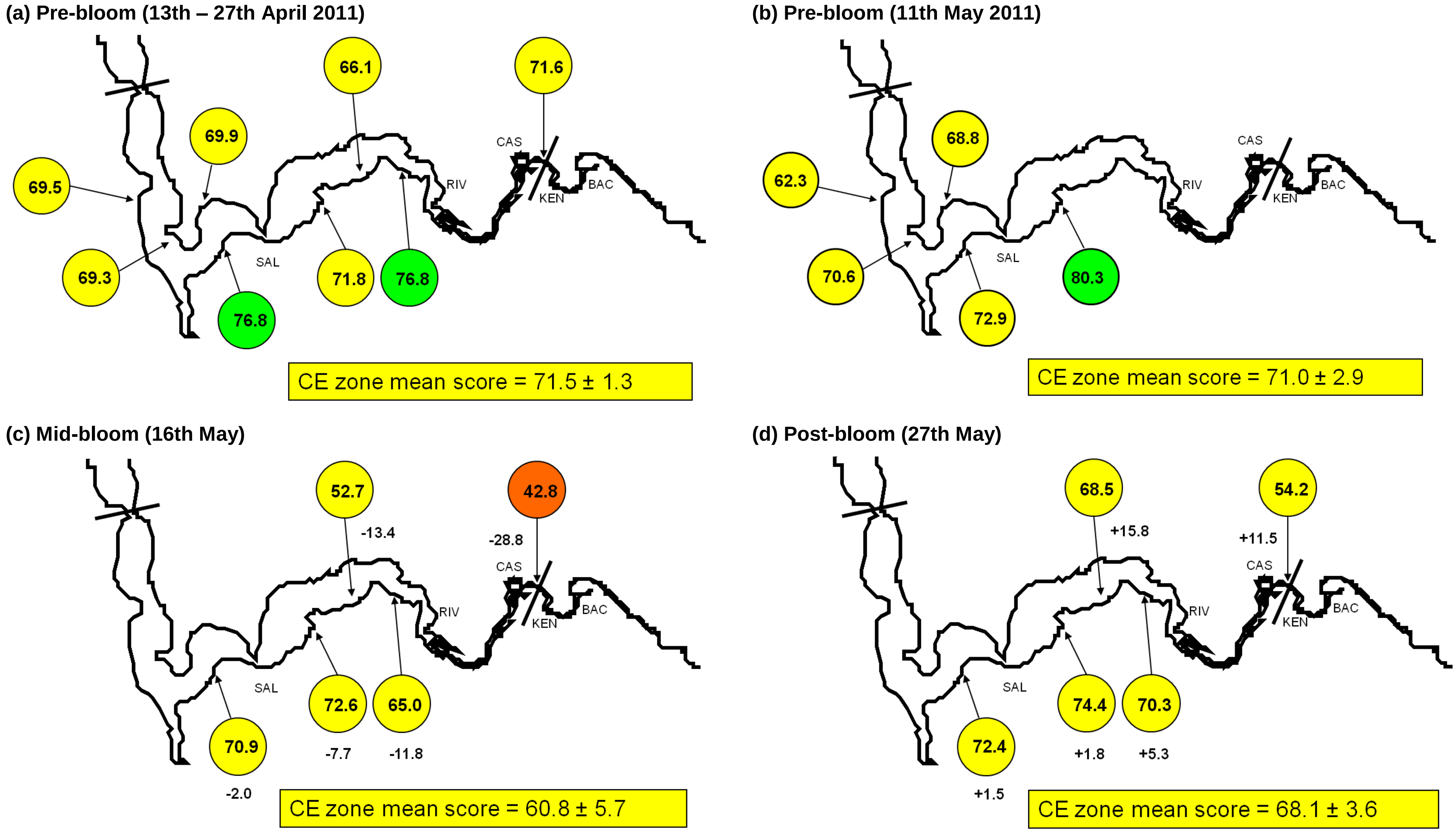


Figure 13. Maps of the Canning Estuary (CE) zone of the Swan-Canning Estuary, illustrating nearshore Fish Community Index scores (circled) and provisional condition classifications (green – good, yellow – fair, orange – poor, red – very poor) for sites sampled before (a, b), during (c) and after (d) a *Karlodinium veneficum* bloom in May 2011. Numbers outside circles illustrate changes in index scores from the previous sampling occasion. Boxed text presents mean index score ± standard error, coloured to reflect the accompanying condition classification for the CE zone.

3.3.2. **Karlodinium veneficum** ***bloom of March 2004***

The nearshore and offshore indices demonstrated clear responses to the *K. veneficum* bloom of March 2004. Mean offshore index scores for sites in each of the lower (LS), middle-downstream (MD) and middle-upstream (MU) regions of the Swan River (Fig. 6), and across these regions as a whole, ranged between *ca* 58 and 65 points in January 2004 (pre-bloom), thereby indicating a fair provisional condition status for these deeper waters at this time. However, in the uppermost region of the tidal Swan River (US), the provisional condition of the offshore waters was poor, as reflected by a mean score of 47 (Fig. 14).

By March of that year, at the mid-point of the bloom, the collective provisional condition of the offshore waters in these four regions had become poor (mean = 45). This deterioration was driven largely by declines in the provisional condition of the MD region to poor status (mean score = 43) and most notably of the MU region (in which the bloom was centred) to very poor status (mean score = 17; Fig. 14). In contrast, the offshore condition of the LS and US regions actually increased slightly between January and March, presumably reflecting the immigration of fish into the refugia of these less bloom-affected areas from the more heavily affected MU and MD regions.

As the intensity of the bloom subsided by April 2004, the offshore scores in each region recovered towards their pre-bloom levels, such that most regions had regained fair provisional condition status by this time (Fig. 14). However, although the mean offshore index score for the MU region had increased by *ca* 31 points between March and April, the provisional condition of this bloom-affected region remained poor (mean = 47.5), suggesting that the negative impacts of the bloom persisted there.

The nearshore index scores responded in a broadly similar way to the offshore scores during this bloom event. The mean nearshore index scores in each of the LS and MD regions were around 74 points in January 2004, indicating that their provisional condition was fair to good prior to the onset of the bloom (Fig. 15). Similarly, the mean index score across all seven of the nearshore sites surveyed at this time (*i.e.* the sites in the LS and MD regions and the single site surveyed in the MU region; see Fig. 6) was also 74.

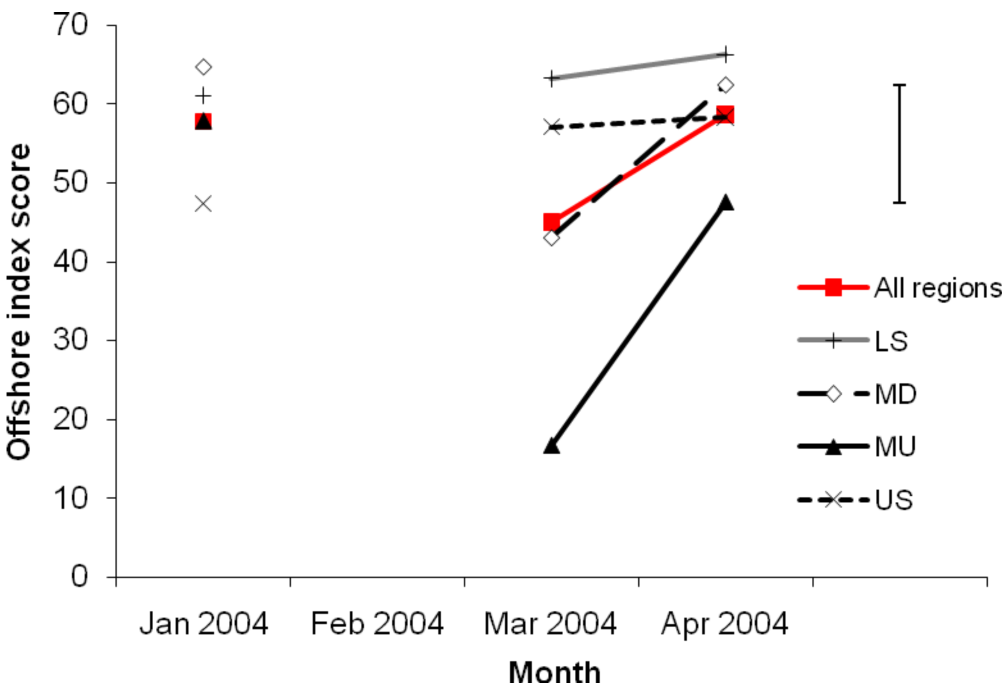


Figure 14. Mean offshore index scores recorded from the Lower (LS), Middle-Downstream (MD), Middle-Upstream (MU) and Upper (US) Swan River regions (and across all of these regions) before, during and after a *Karlodinium veneficum* bloom that occurred in the MU region of the Swan River during early to mid-March 2004. The average standard error observed across all regions and months is plotted for clarity.

By the mid-point of the bloom, the nearshore condition of these regions had declined, both individually and collectively, although the decrease in nearshore scores was less marked than that observed at offshore sites (*cf* Figs. 14 and 15, noting the difference in scale). The condition of nearshore waters in the LS and MD regions thus remained fair at the height of the bloom, with mean scores of 65 and 70, respectively (Fig. 15). This may in part reflect the role provided by these shallower waters as refugia for fish escaping the more highly stratified deeper waters of the bloom-affected MU region at this time (see below). This finding is particularly notable in the case of the single nearshore site surveyed in the MU region, which exhibited an increase in its Fish Community Index score from 72 in January 2004 to 81 in March 2004 as the provisional condition of the adjacent offshore waters plummeted. As the intensity of the bloom subsided by April, the nearshore scores in each region subsequently recovered towards their pre-bloom levels (Fig. 15).

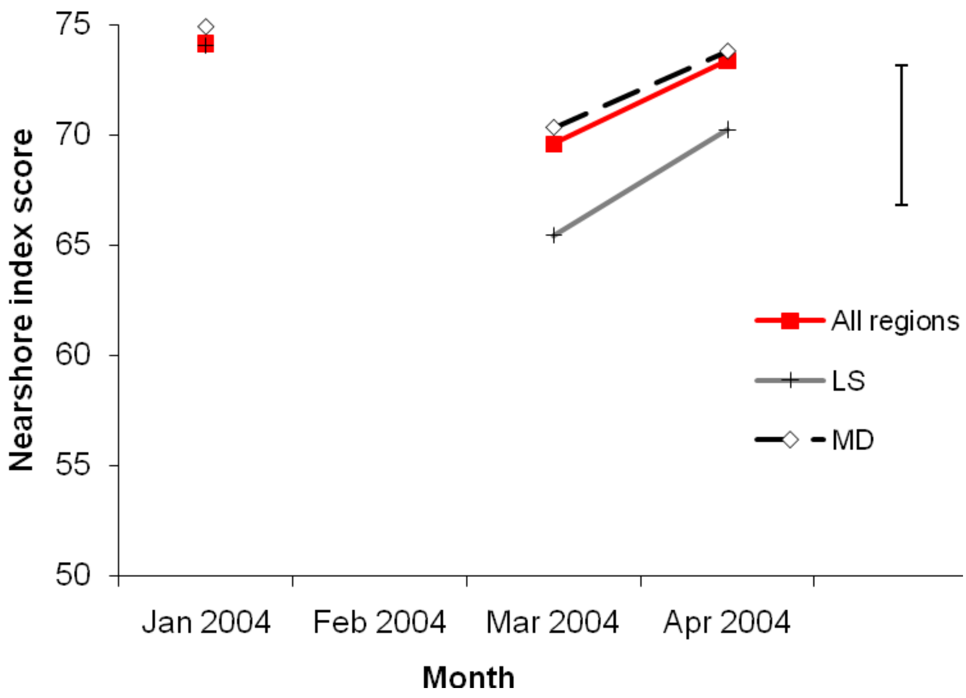


Figure 15. Mean nearshore index scores recorded from the Lower (LS) and Middle-Downstream (MD) Swan River regions (and across all sites) before, during and after a *Karlodinium veneficum* bloom that occurred in the Middle-Upstream (MU) region during early to mid-March 2004. Note the difference in scale from Fig. 14. The average standard error observed across all regions and months is plotted for clarity.

As in the case of the 2011 bloom (section 3.3.1), the observed decrease in index scores during the height of the 2004 bloom, and their subsequent post-bloom recovery, are largely thought to reflect the migration of fish in response to changes in the ecological condition of the bloom-affected areas. For example, Valesini et al. (2005) highlighted substantial evidence that several species that normally occupy the middle to upper reaches of the Swan River during summer and early autumn undertook pronounced movements out of these areas during the 2004 bloom period. Black bream, for example, a relatively large and highly mobile species, was shown to exhibit conspicuous movements downstream to the nearshore waters of the LS region or beyond, and upstream to the deeper, offshore waters of the US. Moreover, three weeks after the peak of the 2004 bloom, Black bream once again characterised the faunas in the most heavily affected MU region, yet no longer characterised those in some of the regions in which it was prevalent during the bloom, indicating recolonisation of the MU region by this species in response to its improving ecological condition (Valesini et al. 2005).

Other authors have noted similar movement responses of fish species to hypoxia and other bloom-related stressors. Potter et al. (1983)

demonstrated that larger and more active fish species moved away from blooms of the blue-green algae *Nodularia spumigena* in the Harvey Estuary, Western Australia. Eby and Crowder (2002) also noted that fish species exhibited behavioural avoidance of hypoxic zones (*i.e.* dissolved oxygen <2 mg/L) in the Neuse River Estuary of North Carolina (USA). Thus, during hypoxic episodes, fish species in the latter system were restricted to its shallower, more highly oxygenated waters. Such 'habitat compression' results in elevated fish densities in refuge areas, and may lead to sublethal physiological effects on fish health and growth, behavioural effects on trophic interactions and further reductions in benthic habitat quality (Eby and Crowder 2002, Eby et al. 2005).

Blooms of *K. veneficum* can be toxic to fish if algal cells lyse and release ichthyotoxins into the water (Hallegraeff et al. 2010). The algae may also adversely affect fish by physically clogging their gills and reducing their ability to visually locate prey. Deoxygenation of the water column, particularly at depth, can occur due to biological oxygen demand of the bloom and associated microbial activity. This is particularly prevalent at night in the absence of photosynthesis. The decomposition of the senescing bloom will also increase biological oxygen demand. It is hypothesised that such effects of the bloom, in concert with the night-time reductions in oxygen concentrations which would have been experienced in the MU Swan River, interacted to reduce the health of this region and caused the emigration of fishes from bloom-affected areas to those upstream and downstream regions which were in comparatively better environmental condition.

However, analyses of the accompanying data for water quality variables collected by the DoW throughout the pre- to post-bloom period in 2004 found no significant differences in these variables over this time frame (see Valesini et al. 2005). Indeed, the concentration of dissolved oxygen (the water quality parameter most likely to impact the survival of fishes during the bloom) at the water surface was **higher** in March than in mid-summer in the MD, MU and US regions, whilst relatively little change in this environmental variable was detected in the bottom waters (Valesini et al. 2005). This is not surprising, as algal cells produce oxygen during daylight hours as a by-product of photosynthesis. In contrast, in the absence of photosynthesis, respiration of algal cells at night will lead to reduced oxygen concentrations in bloom-affected waters, and thus it is at night/daybreak that the effects of algal blooms on fish and other biota are likely to be most severe. Thus, given that the DoW undertakes water quality measurements only during the day, it is highly unlikely that significant correlations between these water quality data and fish responses could be detected.

It is therefore recommended that, if fish (and therefore Fish Community Index) responses to bloom-induced hypoxia are to be identified, water quality parameters should also be measured at night in this system.

4. Review of the Fish Community Index condition grading system

4.1. Rationale and objectives

Multimetric index approaches allow index scores to be converted to qualitative (descriptive) categories or alphanumeric grades, for use in communicating estuarine condition. Appropriate cut-offs or thresholds between grades or categories must thus be determined, and this can be achieved in a variety of ways. The optimal approach for determining thresholds between grades will achieve a balance between index sensitivity (responsiveness) and variability (noise), with the resultant index being sensitive to real changes in the fish communities in response to stressors such as algal blooms, yet sufficiently robust to be relatively unresponsive to natural variability over fine temporal and spatial scales.

The provisional system for determining estuarine condition from index scores, in which the possible range of index scores is subdivided into four descriptive classes of equal breadth (*i.e.* good, fair, poor, very poor; Hallett et al. 2012b), was considered to be potentially skewed toward producing fair to good grades. The following section of the report thus describes a comparative evaluation of alternative systems for determining estuarine condition grades, and aims to determine the optimal grading system for the Fish Community Indices of estuarine condition. This will provide greater confidence in the outputs of the indices and ensure that they are consistent with the needs of proposed Riverpark report cards.

4.2. Methodology

4.2.1. Alternative grading systems considered, and the determination of thresholds

In addition to the provisional classification scheme, three alternative approaches for determining ecological condition from index scores were considered. An ‘historical’ data set of index scores calculated from samples of the nearshore and offshore fish communities collected throughout the Swan-Canning Estuary between 1977 and 2009 was used in determining the grading thresholds under each of these approaches. Note that this data set was the same as that used to select metrics and establish reference conditions for the indices (Hallett 2010, Valesini et al. 2011).

As all historical sampling of the fish community from offshore waters of the Swan-Canning Estuary was carried out using a consistent method and fishing gear, a single historical data set comprising all offshore index scores recorded between 1978 and 2009 was used in regrading of the offshore index. In contrast, several different seine net gears have been used historically to sample the nearshore fish communities of the Swan-Canning Estuary, necessitating the standardisation of catches using alternative gears to a common standard, namely a seine net 21.5 m in length (see Hallett and Hall [2012] for a full description of these sampling gears and standardisation approaches). Therefore, two alternative historical data sets were trialled in regrading of the nearshore index and their resultant outputs compared; a 'full historical data set' of index scores from all samples collected between 1977 and 2009 using all seine net gears (scores having been calculated from fish species abundance data that first had been standardised as described in Hallett and Hall [2012]), and a '21.5 m historical data set' of index scores from samples collected between 1977 and 2009 using only the 21.5 m seine net.

Each of the following alternative grading/classification systems was trialled for both the offshore and nearshore indices:

- **'Distribution test classification system'**: A descriptive system for comparing ecological condition against that which has been previously observed. This approach entailed the use of non-parametric, two-way Wilcoxon Rank Sum tests to compare the distribution of 'sample' index scores (those observed in a period of interest, *e.g.* a given monitoring year) against the distribution of 'historical' index scores. Scores from two 'sample' years of interest (2011 and 2012) were compared to those from the historical data sets in this way, with Bonferroni correction being applied to correct the value of p for repeated testing, in order to trial and evaluate this approach.
- **'Equal quintile-based grading system'**: An alphanumeric grading system with five grades (A-E) representing good to poor ecological condition, respectively, in which grade boundaries were determined by dividing the index scores from the historical data sets into five equal quantiles (*i.e.* quintiles), each containing 20% of the observed scores.
- **'Unequal quantile-based grading system'**: An alphanumeric grading system with five respective grades (A-E) representing good to poor ecological condition, in which the boundaries for grades A and E comprised the 90th and 10th percentiles, respectively, of the index scores from the historical data sets. The intermediate grades B-D were determined by dividing the remaining 80% of index scores from historical fish community samples into three equal quantiles, each containing 26.67% of the observed scores.

The above analyses were performed for the estuary as a whole, rather than for individual estuarine management zones, as common grade boundaries would ensure that ecological condition could be compared reliably among management zones.

4.2.2. Validation of resultant index sensitivity and robustness

Each of the alternative grading approaches outlined above was then evaluated by examining their effects on the sensitivity and robustness of the nearshore and offshore indices. A separate 'validation' data set of index scores calculated from samples of the nearshore and offshore fish communities collected throughout the Swan-Canning Estuary between January 2011 and May 2012 was used for this purpose. This data set was collected and derived as described in section 2.1 of the current report.

Effects on nearshore index sensitivity were determined by comparing the ecological condition grades for samples collected prior to, during and after the *K. veneficum* bloom which occurred in the CE zone during May 2011 (section 2.5.1.). Note that the sensitivity of the offshore index could not be assessed in this manner due to a lack of repeated sampling of the CE zone during and after the May 2011 bloom.

The robustness of each of the alternative grading systems for the nearshore and offshore indices was assessed by examining temporal patterns in the ecological condition outputs for the estuary as a whole, from nearshore and offshore samples collected between summer 2011 and autumn 2012.

The relative merits and disadvantages of the alternative grading/classification approaches were then evaluated and the optimal grading approach, to be recommended for future implementation of the Fish Community Indices, was determined as that which resulted in indices that:
(i) are sufficiently sensitive to be able to communicate the changes in fish communities caused by stressors such as algal blooms,
(ii) are sufficiently robust to withstand the effects of natural variability (*i.e.* are not overly affected by 'noise'), and
(iii) provide a flexible, informative and easily understood means of visually communicating ecological condition (preferably one which is consistent with the requirements of proposed report cards for the Swan-Canning Riverpark).

4.3. Results and discussion

4.3.1. Existing, provisional classification system

The provisional system for classifying ecological condition as good, fair, poor or very poor was confirmed as being skewed toward producing fair to good classifications, with the large majority of both nearshore and offshore historical samples being categorized as fair (Fig. 16). Similarly, 90% and 73% of the respective nearshore and offshore scores from the 2011-2012 validation data sets fell in the top two categories (good, fair), with almost no samples allocated to very poor condition. These results highlight a limitation of the provisional scheme, in that an assessment of very poor condition would be made only on the very rare occasions on which an extremely low index score (<25) was observed. Thus, the provisional scheme is far from optimal as a management tool, and an alternative grading system is merited.

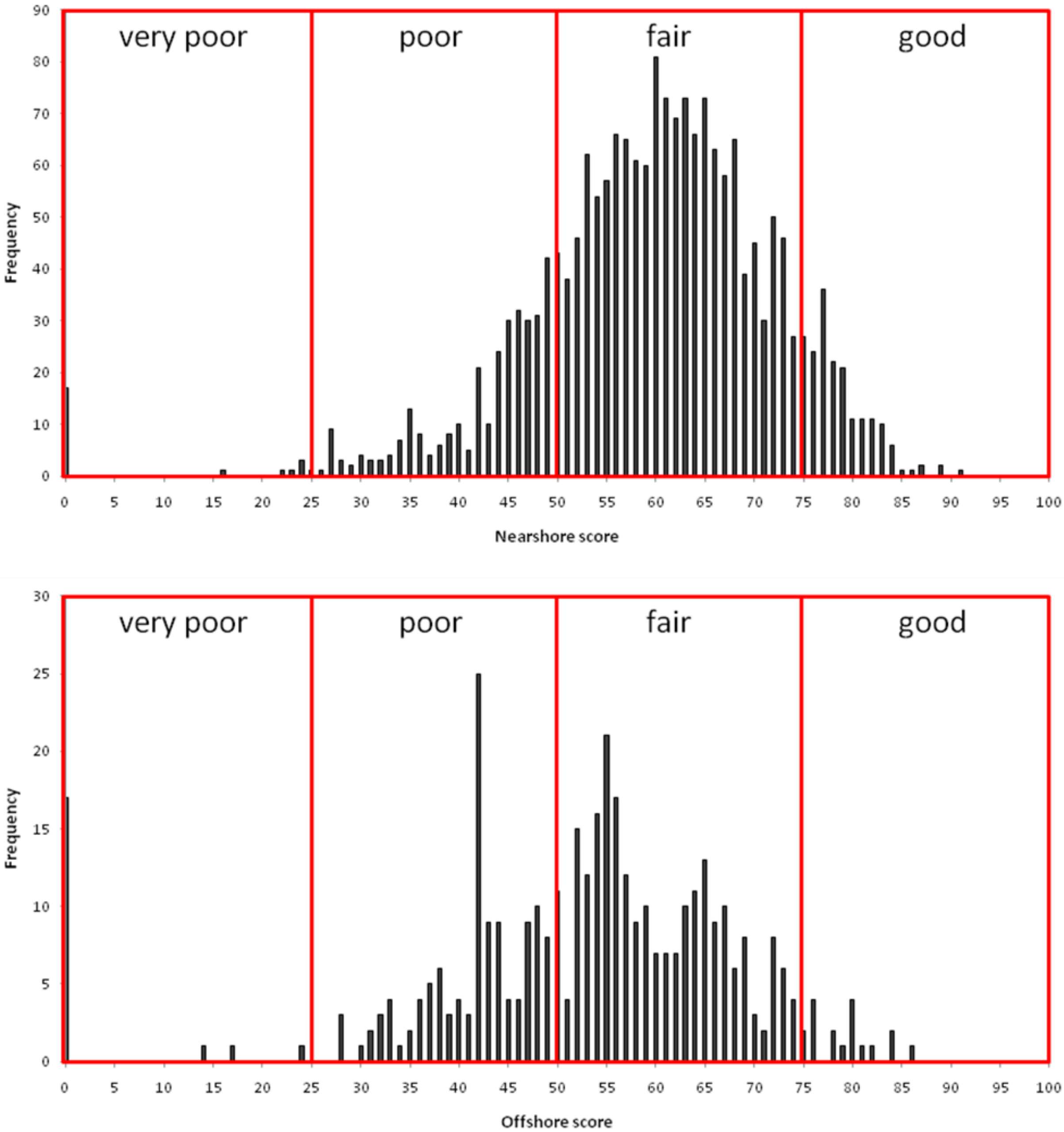
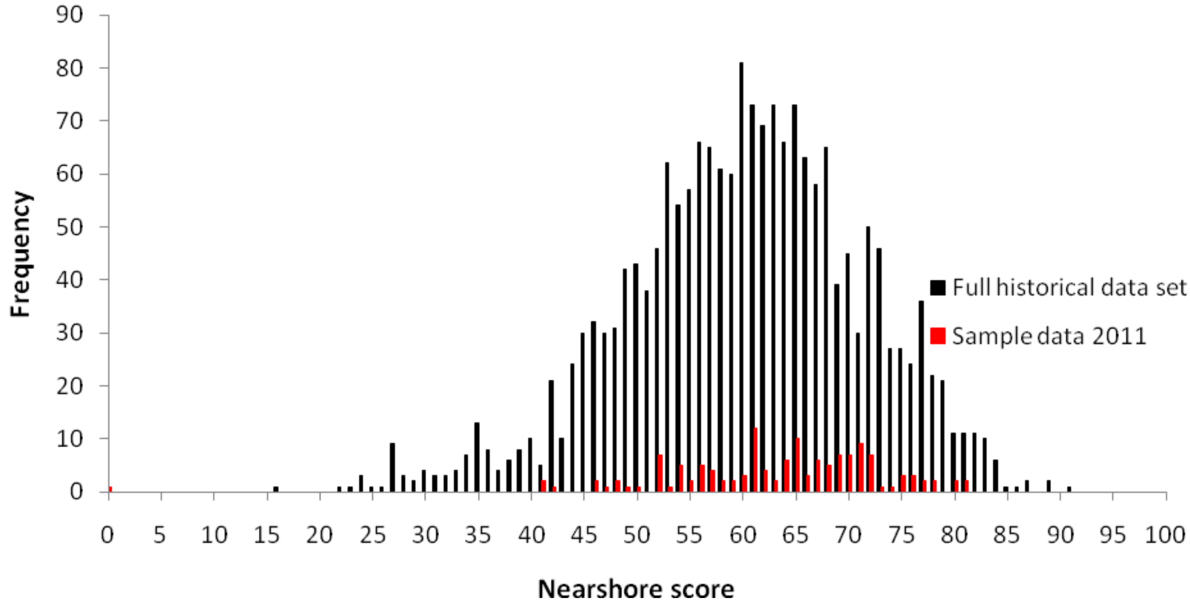


Figure 16. Frequency distributions of nearshore (upper plot) and offshore (lower plot) Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data sets). Provisional condition classifications and thresholds are shown in red.

4.3.2. 'Distribution test classification system'

Nearshore index:

The distributions of nearshore index scores comprising the full and 21.5 m historical data sets were broadly similar, with respective median scores of 61.0 and 60.4. Both distributions appeared to approximate normality yet had notable 'tails' of scores <40 (*cf.* Figs. 17 and 18).



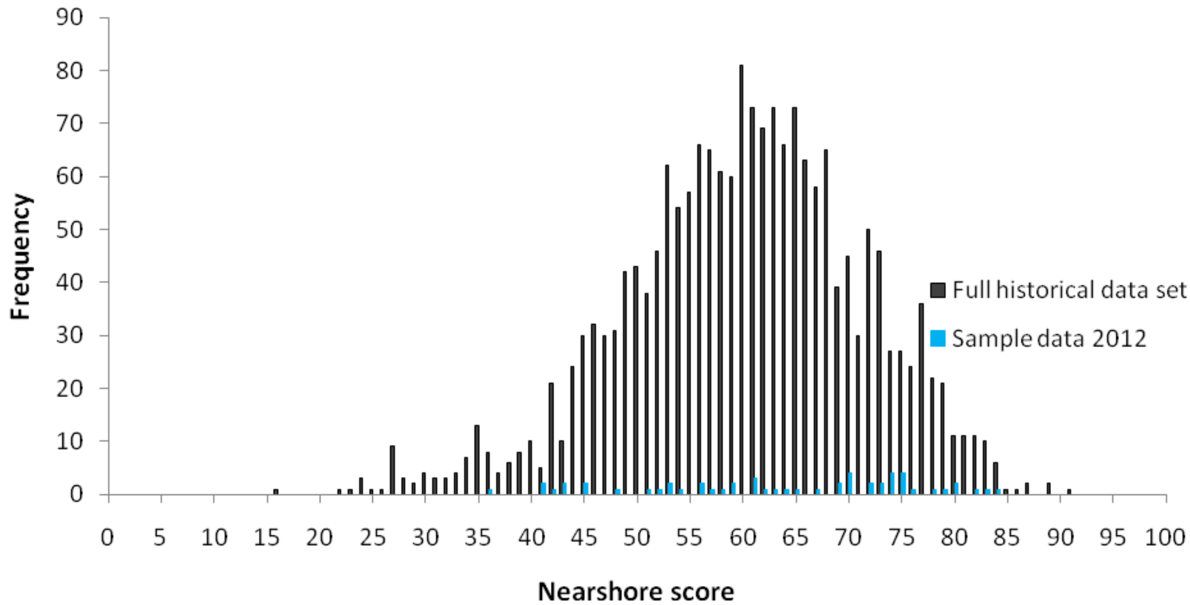


Figure 17. Frequency distributions of nearshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data set; black; *n* = 1,930) and of nearshore index scores from samples collected during the 2011 (red; *n* = 136) and 2012 (blue; *n* = 54) monitoring/validation years.

The distributions of nearshore index scores in the sample years 2011 and 2012 appeared markedly different in shape from those of both historical data sets, with their flatter distributions and smaller ranges reflecting in part their far smaller sample sizes (Figs. 17 and 18). The respective median nearshore index scores recorded in 2011 and 2012 were 65.1 and 66.5, respectively, both of which exceeded the median scores of 61.0 and 60.4 for the full and 21.5 m historical data sets.

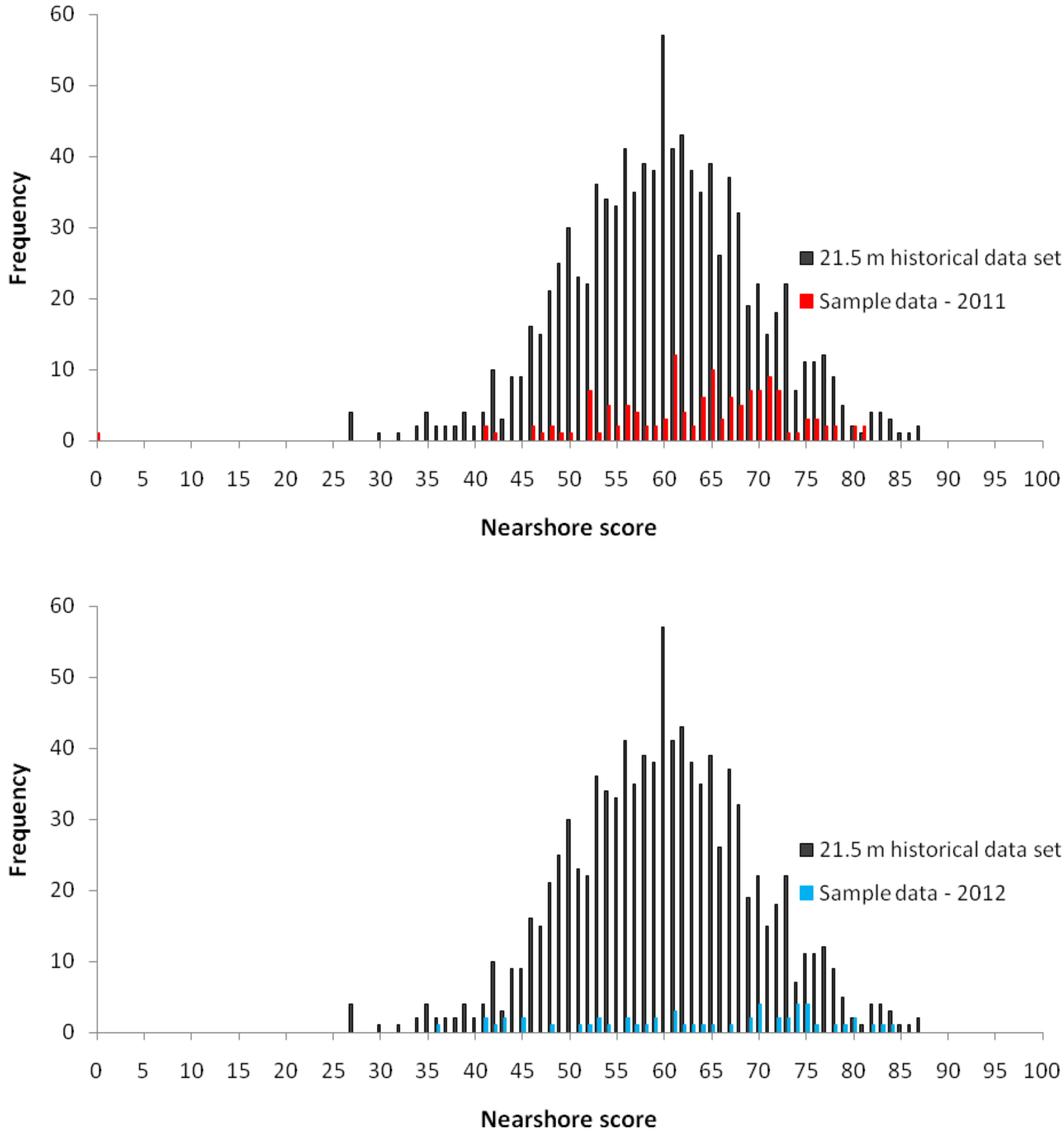


Figure 18. Frequency distributions of nearshore Fish Community Index scores from samples collected between 1977 and 2009 in the Swan-Canning Estuary using a 21.5 m seine net (21.5 m historical data set; black; *n* = 987) and of nearshore index scores from samples collected during the 2011 (red; *n* = 136) and 2012 (blue; *n* = 54) monitoring/validation years.

The distributions of nearshore scores from both 2011 (Wilcoxon W = 83612.5, n_{2011} = 136, $n_{21.5\ m}$ = 987, p <<0.0001) and 2012 (Wilcoxon W =

32648, n_{2012} = 54, $n_{21.5\ m}$ = 1930, p = 0.0053) differed significantly from that of the 21.5 m historical data set. In contrast, whilst the distribution of nearshore scores from 2011 also differed significantly from that of the full historical data set (Wilcoxon W = 157233, n_{2011} = 136, n_{full} = 1930, p = 0.0001), no significant difference was detected between the distribution of nearshore scores from 2012 and that in the full historical data set (Wilcoxon W = 62435, n_1 = 54, n_2 = 1930, p = 0.0129), although this result was close to statistical significance at the Bonferroni-corrected level of p = 0.0125. Taken together with the relevant median scores, these results might suggest that the nearshore scores from 2011 and 2012 were slightly greater than those observed historically, and thus that the ecological condition of the estuary in each of the two sample years could be reported as being 'significantly better than that which has been observed historically, on average'.

However, given the differences not only in the apparent locations of the distributions but also, as noted above, in their shape, it is crucial to stress a caveat concerning the use of the distribution test classification system as described above. The Wilcoxon Rank Sum test is sensitive not only to differences in the locations of two distributions, but also to differences in their shape (Quinn and Keough 2002). Thus it is not valid simply to state that the above results show one set of scores to be statistically greater than another; it can only be stated that the distributions are statistically different in some way. Clearly this will limit the utility of the proposed distribution test classification system for assessing and reporting ecological condition.

Offshore index:

The respective median offshore index scores recorded in the sample years of 2011 and 2012 were 60.0 and 59.5, both of which differed markedly from the median score of 55.1 for the full historical offshore data set. The distributions of offshore scores from each of the two sample years differed significantly from that of the full historical offshore data set (2011 - Wilcoxon W = 22342, n_{2011} = 92, n_{full} = 395, p = 0.0006; 2012 - Wilcoxon W = 12871, n_{2012} = 54, n_{full} = 395, p = 0.01364; Fig. 19). On face value, these results might suggest that the ecological condition of offshore waters throughout the Swan-Canning Estuary was, on average, significantly better in both 2011 and 2012 than had been observed historically. However, it must again be noted that the caveat raised above makes the validity of such an interpretation questionable.

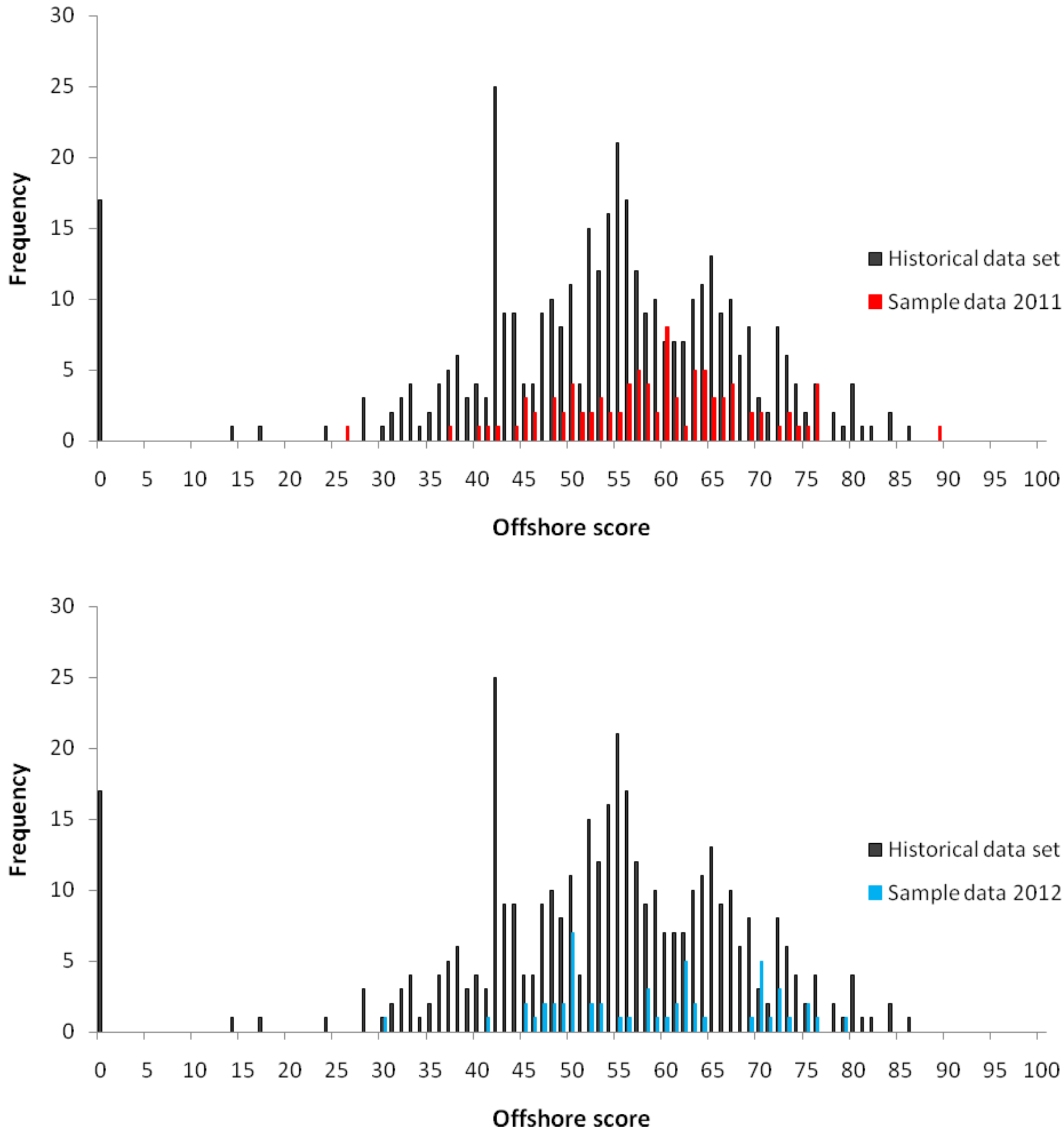


Figure 19. Frequency distributions of offshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (historical data set; black; *n* = 395) and of offshore index scores from samples collected during the 2011 (red; *n* = 92) and 2012 (blue; *n* = 54) monitoring/validation years.

The assumptions and limitations of the statistical tests outlined above limit the utility of the distribution test classification system for assessing and reporting ecological condition. Moreover, whilst the outputs of this system provide some measure of statistical inference about ecological condition, the most that can be concluded and reported is that ecological condition is 'significantly better than', 'significantly worse than', or 'not significantly different from' that which has historically been observed. This system therefore offers relatively little resolution of the ecological condition of the estuary, is not particularly informative as a means of communicating with the public, and does not accord with the alphanumeric grading systems proposed for other component indices of future report cards for the Riverpark. Given these limitations, we conclude that such a system for assessing ecological health is far from optimal as a management tool, and an alternative grading system would be preferable.

4.3.3. 'Equal quintile-based grading system'

Nearshore index

Rather than the arbitrarily-chosen thresholds between condition categories, this system sought to define grade boundaries based on the observed distributions of historical index scores, with the five grades being equivalent to the five equal quintiles into which the historical data distribution could be split. The resulting nearshore grade boundaries differed markedly from those between the four condition classifications of the provisional scheme, with the lowest grade (E) being defined by scores of less than *ca.* 51-52 points, depending on the historical data set employed (Fig. 20, Table 5), as opposed to scores of <25 points being classed as 'very poor' under the provisional scheme. The highest grade (A) boundary, being defined by scores of *ca.* 68-70, was not too dissimilar to the 'good' classification awarded to scores >75 under the provisional scheme. The most noticeable difference was the far narrower ranges of scores representing each of the intermediate grades B, C and D, compared to those representing 'fair' and 'poor' condition under the provisional system (Fig. 20).

The use of different historical data sets had a slight yet noticeable effect on the nearshore grade boundaries under the equal quintile-based grading system, with those boundaries based on the full historical data set being slightly more extreme, *i.e.* higher boundaries for high grades and lower boundaries for the low grades (Table 5). The effect of these differences was that around 12% of the condition grades awarded to the 190 nearshore samples in the 2011-12 validation set changed as a result of restricting the historical data to 21.5 m seine net samples only, with some C grades becoming B grades and Bs becoming As, whilst some D grades were regraded to E upon use of the restricted, 21.5 m data set.

The equal quintile-based grading systems were both far less skewed toward producing high grades than the provisional classification scheme. Whereas fewer than 10% of the 190 samples in the validation data set received poor or very poor classifications under the provisional scheme (and only one of which was classed as very poor), the bottom two grades under the equal quintile-based grading system accounted for *ca.* 27% of samples in the validation data set. The quintile-based grading system thus possesses greater apparent sensitivity to ecological condition than the provisional system.

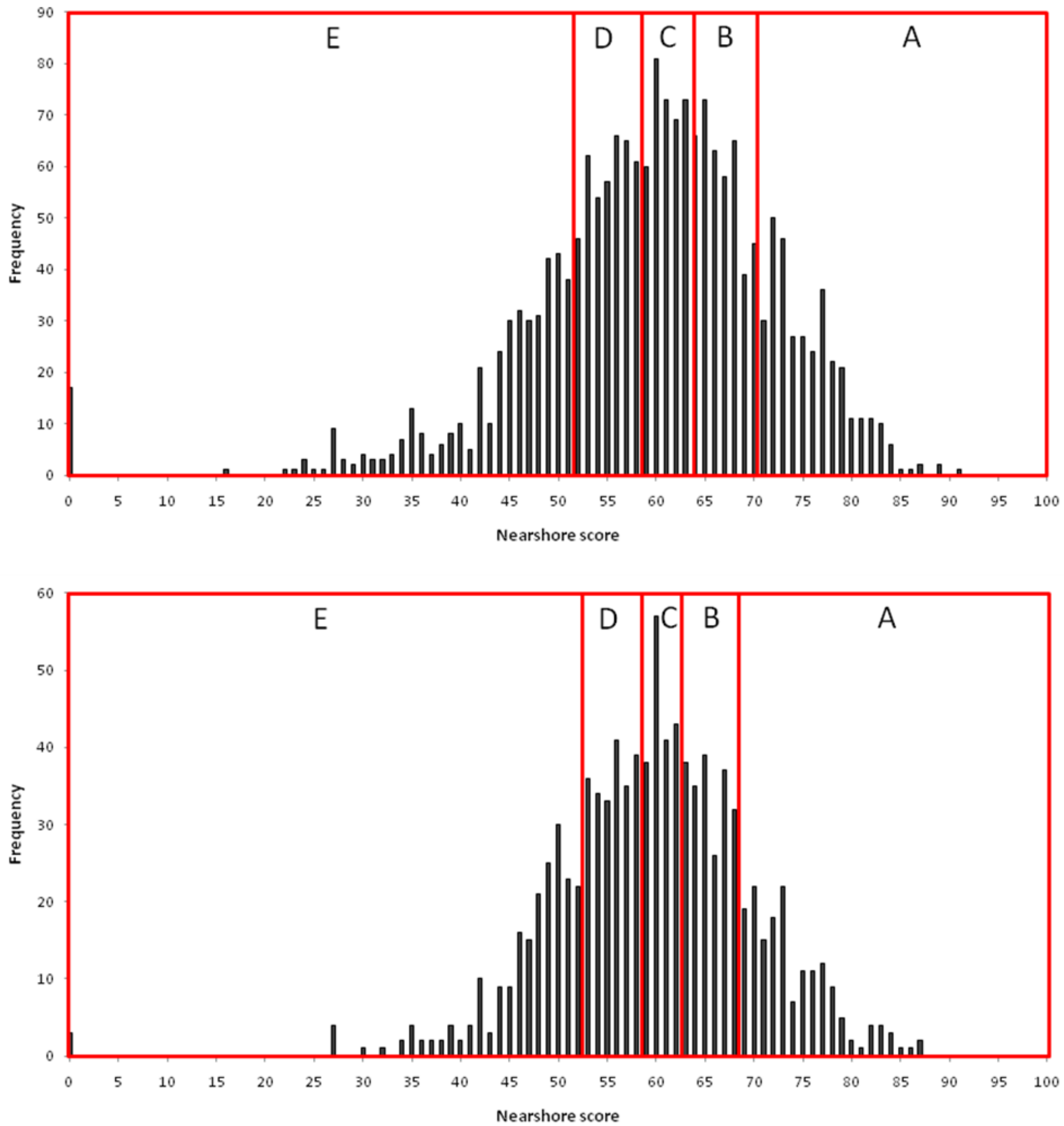


Figure 20. Frequency distributions of nearshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data set; upper plot) and from samples collected over the same period using a 21.5 m seine net (21.5 m historical data set; lower plot). Boundaries for ecological condition grades A-E, determined under the equal quintile-based grading system, are shown in red.

Table 5. Fish Community Index scores comprising each of the five condition grades for nearshore waters, as defined using an equal quintile-based grading system based on each historical nearshore data set. The percentage of samples in the 2011-12 validation data set (*n* = 190) awarded each grade is also shown for each grading scheme.

Condition grade	*Full historical data set*		*21.5 m historical data set*	
	Scores	**Validation %**	**Scores**	**Validation %**
A	>69.9	33.2	>68.1	40.5
B	63.7-69.9	22.1	62.5-68.1	17.4
C	58.1-63.7	17.4	58.0-62.5	14.7
D	51.2-58.1	16.8	52.3-58.0	14.7
E	<51.2	10.5	<52.3	12.6

It is crucial to note at this point the use of the term 'apparent sensitivity'. The true sensitivity of the Fish Community Indices (or any other similar measure) is a characteristic of the index scores, and not of their condition classifications or grades. The former are based directly and objectively upon fish species abundance data collected during field sampling, such that a decrease in index scores reflects a putative response of the fish community to a decline in (some aspect[s] of) the ecological condition of the estuary: the larger the decrease in score, the larger the indicated decline in condition. *An index is insensitive only if its scores exhibit no response to a measurable ecological perturbation*. In contrast, condition grades are a somewhat arbitrary, subjective interpretation of what the index scores tell us about ecological condition, and are dependent on the grading scale employed. By way of example, suppose we were to develop a theoretical 0-100 scoring scheme that had only two grades/classifications (*e.g.* 'high', 'low') separated by a boundary score of 50 points, and a second scheme with ten grades separated by boundaries every 10 points. Two samples which returned respective index scores of 95 and 51 before and after an ecological perturbation would both receive the same 'high' classification under the former scheme but would be separated by five grades under the latter. In such an instance, the sensitivity of the index to the ecological perturbation has not changed, but the ability of our classification/grading scheme to effectively communicate the extent of the perturbation (its 'apparent sensitivity') has.

Accepting the above distinction, the quintile-based grading system possesses greater apparent sensitivity to ecological condition than the provisional system as its five grades and percentile-based boundaries enable spatial and temporal differences in ecological condition to be communicated with greater resolution. This is confirmed by patterns in the ecological condition grades observed across sites in the CE before, during and after the

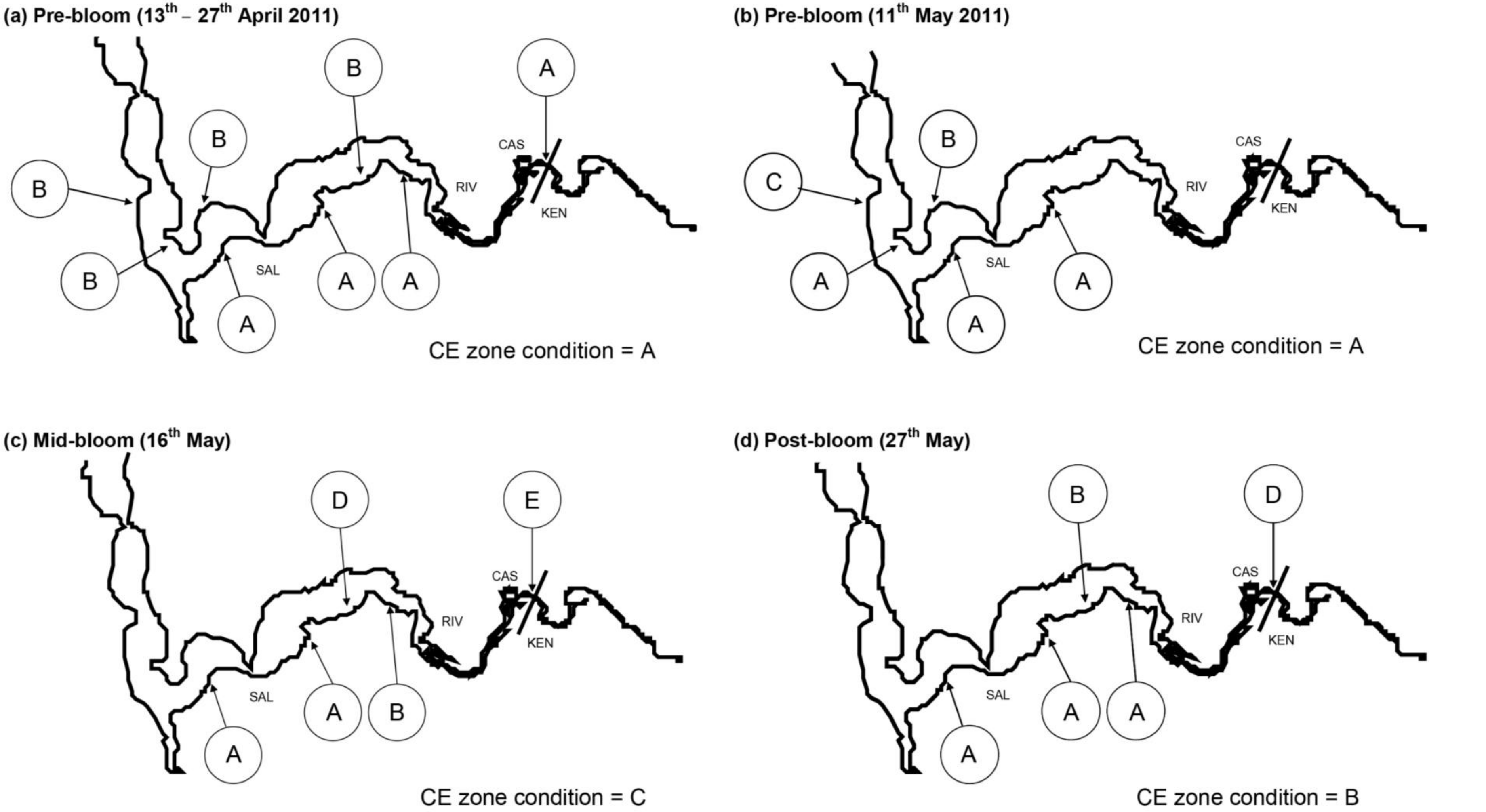


Figure 21. Maps of the Canning Estuary (CE) zone of the Swan-Canning Estuary, illustrating nearshore Fish Community Index condition grades (A-E; derived via the 'equal-quintile-based grading system' applied to the full historical nearshore data set) for sites sampled before (a, b), during (c) and after (d) a *Karlodinium veneficum* bloom in May 2011. Overall condition grade for the CE zone, based on the mean index score across sites, is also shown.

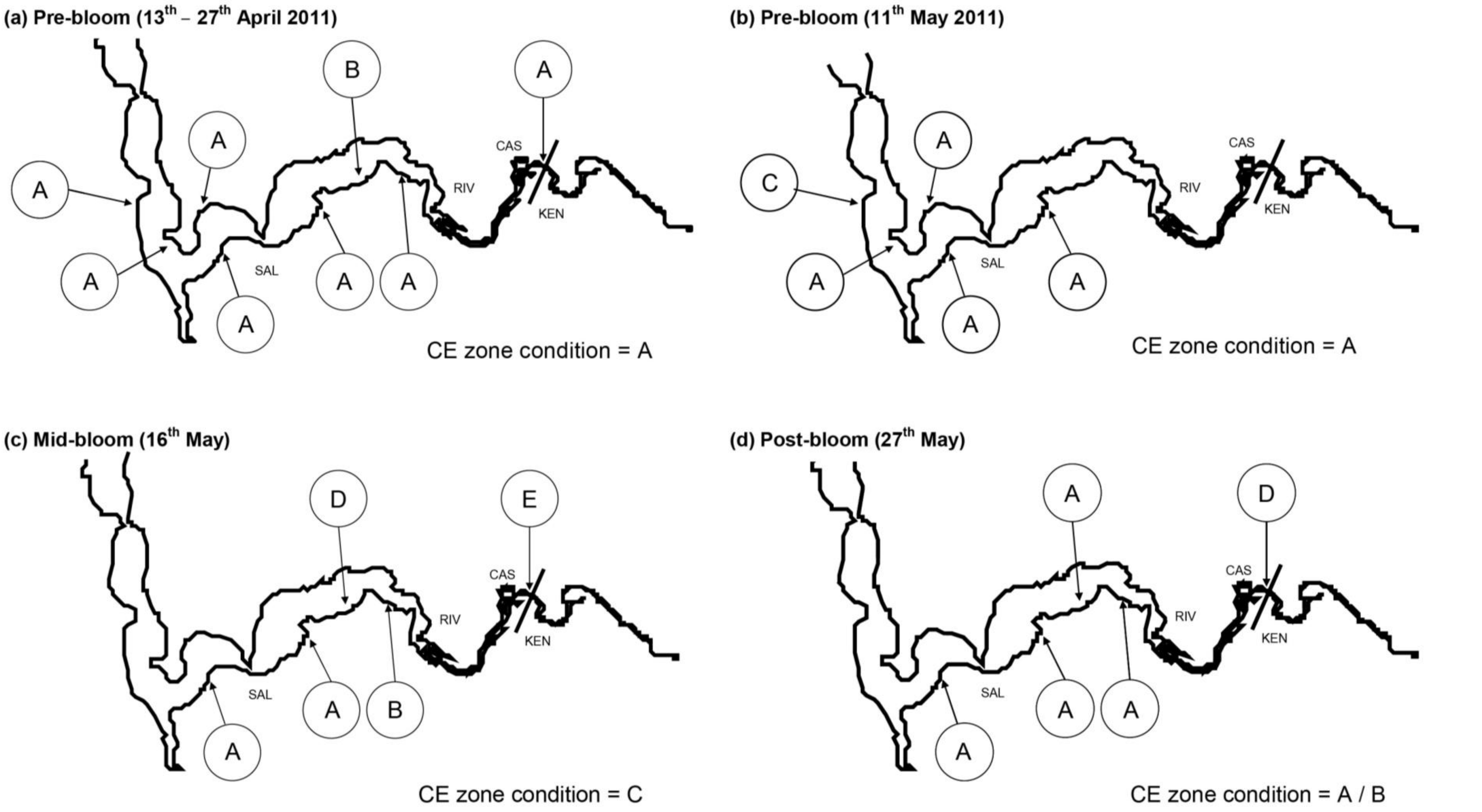


Figure 22. Maps of the Canning Estuary (CE) zone of the Swan-Canning Estuary, illustrating nearshore Fish Community Index condition grades (A-E; derived via the 'equal-quintile-based grading system' applied to the 21.5 m historical nearshore data set) for sites sampled before (a, b), during (c) and after (d) a *Karlodinium veneficum* bloom in May 2011. Overall condition grade for the CE zone, based on the mean index score across sites, is also shown.

May 2011 *K. veneficum* bloom. Based on grade boundaries established using both historical data sets, the overall ecological condition of the CE during late April 2011 received a grade A, with each individual site being graded A or B (Figs. 21 and 22). As of May 11th the overall condition of this zone had not changed, despite a change of grade for a few sites, yet by May 16th the ecological condition of some sites had decreased to a D or E grade and the overall condition of the zone had declined by two grades as a result of the bloom. Following the collapse of the bloom the condition of the CE zone subsequently recovered to its pre-bloom grade of A (or to the threshold between A and B grades in the case of the grading scheme based on the 21.5 m historical data set; Fig. 22). The equal quintile-based grading system thus provides better resolution of changes in the ecological condition both of individual sites and of entire zones, than did the provisional classification system.

The potential weakness of a grading scheme which provides a high degree of resolution of spatial and temporal differences in ecological condition is that such a scheme may be unduly responsive to 'noise', *i.e.* exhibit a high degree of variability in response to natural variability among fish communities, as small changes in index scores lead to frequent changes in condition grades. It can be seen, however, that the grading systems based on equal quintiles also produce a relatively robust index. The condition grades of a few sites in the CE zone were observed to change between sampling occasions in the weeks preceding the bloom, but the overall condition for the zone did not change in this time (Figs. 21 and 22 a and b).

Similarly, the ecological condition grades awarded to each zone were relatively consistent across repeated sampling occasions within and between seasons in both 2011 and in 2012, with the majority of grades staying the same or changing by only one grade (Table 6). This was the case for the systems based on both the full and 21.5 m historical data sets, both of which returned generally similar grades. Of the two equal quintile-based grading systems, that employing the full historical data set was the slightly more conservative of the two, returning lower grades for some zones on some occasions. It is notable that both systems identified particularly low ecological condition (grade D) for the nearshore waters of the USE in May 2011 and summer 2012, and of the LSCE zone in autumn 2012.

Table 6. Nearshore condition grades (A-E, as determined from mean index scores under the equal quintile-based grading system using each historical data set) for zones of the Swan-Canning Estuary during repeated sampling occasions in 2011 and 2012.

Estuary Zone	*Full historical data set*						*21.5 m historical data set*					
	Su 2011		**Au 2011**		**Su 2012**	**Au 2012**	**Su 2011**		**Au 2011**		**Su 2012**	**Au 2012**
	Mth 1	Mth 2	Mth 1	Mth 2			Mth 1	Mth 2	Mth 1	Mth 2		
LSCE	A	C	B	C	A	D	A	B	B	C	A	D
CE	C	C	A	B	B	B	C	C	A	A	B	B
MSE	C	C	C	B	B	B	C	C	B	B	A	B
USE	B	A	C	D	D	A	B	A	B/C	D	D	A
Estuary	**B**	**B**	**B**	**C**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**

Offshore index:

The offshore grade boundaries determined using the equal quintile-based grading system again differed markedly from those of the provisional classification scheme. This was most notable in the case of the lowest grade boundary, with the E grade being defined by scores of less than *ca.* 43 points (Fig. 23, Table 7), considerably higher than the boundary score of <25 for very poor condition under the provisional scheme. The grade boundaries for the offshore index were, however, notably lower than their nearshore equivalents (*cf.* Tables 5 and 7), reflecting the lower index scores that have historically been observed for samples taken from deeper, offshore waters in this system.

Table 7. Fish Community Index scores comprising each of the five condition grades for offshore waters, as defined using an equal quintile-based grading system based on the historical offshore data set. The percentage of samples in the 2011-12 validation data set (*n* = 146) awarded each grade is also shown.

Condition grade	Scores	Validation %
A	>65.8	24.7
B	57.1-65.8	34.2
C	52.5-57.1	12.3
D	42.9-52.5	24.0
E	<42.9	4.8

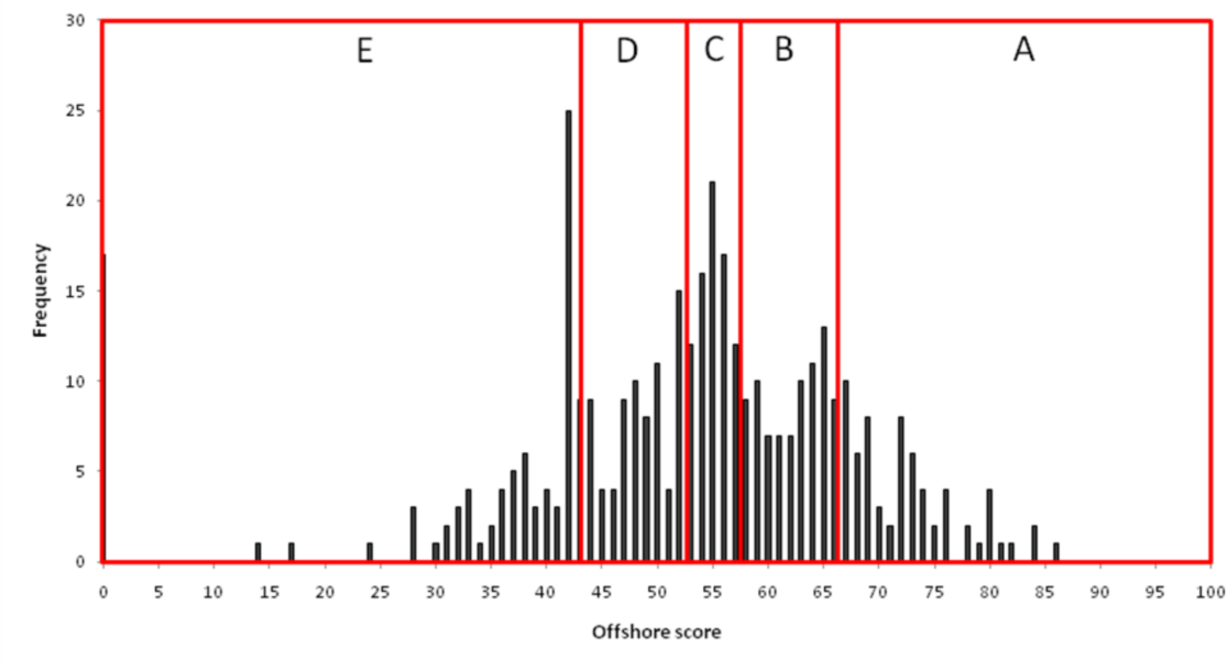


Figure 23. Frequency distribution of offshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data set). Boundaries for ecological condition grades A-E, determined under the equal quintile-based grading system, are shown in red.

The ranges of scores representing each of the intermediate grades B, C and D under the equal quintile-based grading systems were again much narrower than those representing 'fair' and 'poor' condition under the provisional system (Fig. 23). As a result, the quintile-based system was again far less skewed toward certain grades than the provisional classification scheme. More than 73% of the 146 offshore samples in the 2011-12 validation data set received a poor classification under the provisional scheme whilst only 4% were classified as good condition and none as very poor. In contrast, under the equal quintile-based grading system considered here, the top four grades were each awarded regularly across samples comprising the validation data set and 5% received the lowest grade (Table 7), highlighting the far greater ability of the quintile-based grading system to identify and communicate the full range of ecological condition exhibited throughout the Swan-Canning Estuary over time and space.

The grades characterizing the ecological condition of the offshore waters of each zone were less consistent across repeated sampling occasions than were those for the nearshore waters (*cf.* Tables 6 and 8). In several instances the ecological condition of a given zone changed by more than one grade between successive months, although it is not possible to determine with any certainty whether this represents a genuine response to an ecological perturbation or a response to natural variability. It is notable, however, that poor ecological condition (grade D) was identified in the offshore waters of particular zones on several occasions during 2011-12, including the CE zone on more than one occasion (Table 8).

Table 8. Offshore condition grades (A-E, as determined under the equal quintile-based grading system using the historical data set) for zones of the Swan-Canning Estuary during repeated sampling occasions in 2011 and 2012.

	Full historical data set					
Estuary Zone	**Su 2011**		**Au 2011**		**Su 2012**	**Au 2012**
	Mth 1	Mth 2	Mth 1	Mth 2		
LSCE	B	A	B	C	A	A
CE	B/C	D	C/B	C	D	C
MSE	A	B	D	B/C	B	B
USE	B/A	B	B	D	B	B
Estuary	**B**	**B**	**B/C**	**C**	**B**	**B**

4.3.4. 'Unequal quantile-based grading system'

Nearshore index:

The pattern of nearshore grade boundaries generated using this system was fairly similar to that arising from the equal quintile method, although the grade boundaries themselves were more extreme, *i.e.* higher boundaries for high grades and lower boundaries for the low grades (*cf.* Tables 5 and 9). As a result, the respective boundary scores of 74.5 and 45.5 points for grades A and E under the unequal quantile scheme with the full historical data set (Table 9) were the highest and lowest, respectively, of the four alternative, percentile-based grading systems considered. Moreover, the three intermediate grades were defined by a broader range of scores than under the equal quintile method (Fig. 24).

Consequently, the unequal quantile-based grading systems also were both far less skewed toward producing high grades than the provisional classification scheme. All five grades were awarded regularly across samples comprising the validation data set, highlighting again the far greater apparent sensitivity of the unequal quantile-based grading system. Whereas fewer than 10% of the 190 samples in the validation data set received poor or very poor classifications under the provisional scheme (and only one of which was classed as very poor), the bottom two grades under the more extreme of the two unequal quantile-based grading systems accounted for *ca.* 25% of samples in the validation data set (Table 9).

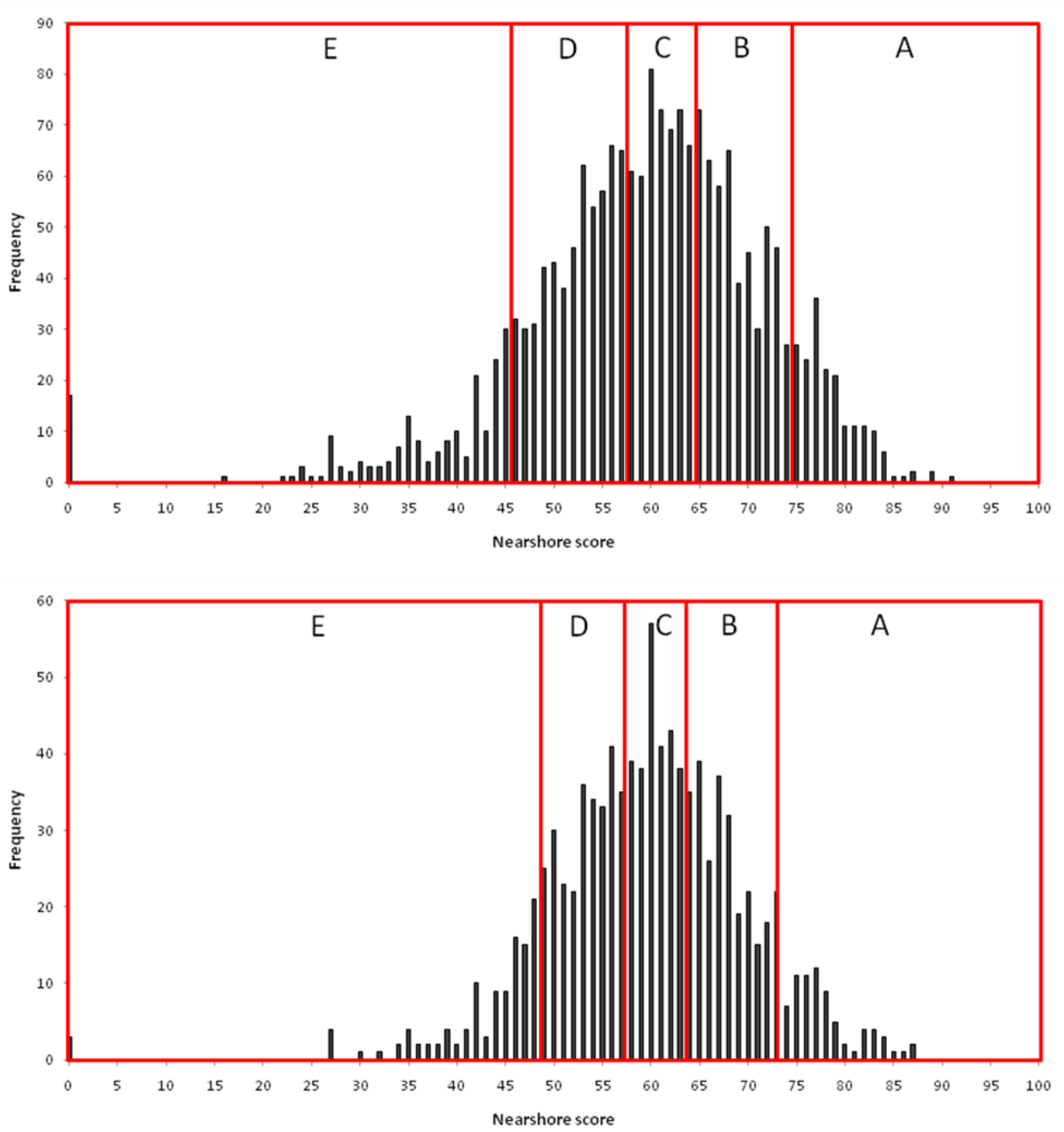


Figure 24. Frequency distributions of nearshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data set; upper plot) and from samples collected over the same period using a 21.5 m seine net (21.5 m historical data set; lower plot). Boundaries for ecological condition grades A-E, determined under the unequal quantile-based grading system, are shown in red.

Table 9. Fish Community Index scores comprising each of the five condition grades for nearshore waters, as defined using an unequal quantile-based grading system based on each of the historical nearshore data sets. The percentage of samples in the 2011-12 validation data set (*n* = 190) awarded each grade is also shown for each grading scheme.

Condition grade	*Full historical data set*		*21.5 m historical data set*	
	Scores	**Validation %**	**Scores**	**Validation %**
A	>74.5	14.7	>72.7	20.0
B	64.6-74.5	37.9	63.3-72.7	35.8
C	57.1-64.6	22.6	57.1-63.3	19.5
D	45.5-57.1	18.9	48.3-57.1	16.3
E	<45.5	5.8	<48.3	8.4

More striking than any differences in the grade outputs between the two unequal quantile-based schemes (*i.e.* full *vs* 21.5 m data sets) are those between the unequal quantile- and equal quintile-based grading approaches. In general, the condition of the CE zone was rated more highly by the system based on equal quintiles, with those sites which were relatively unaffected by the bloom commonly receiving A grades (Figs. 21 and 22) than by that based on unequal quantiles, under which B grades were more common (Figs. 25 and 26). Moreover, the differences in grade boundaries between the two systems resulted in the overall condition of the zone prior to the bloom receiving a lower grade under the latter scheme, compared to the former (A *vs* B, respectively). This result reflects the more extreme grade boundaries of the unequal quantile-based system, such that higher index scores must be observed in order for an A grade to be awarded. As a result, the unequal-quantile system may be considered to be a more conservative assessment tool, yet one which retains the sensitivity to identify cases of high ecological condition.

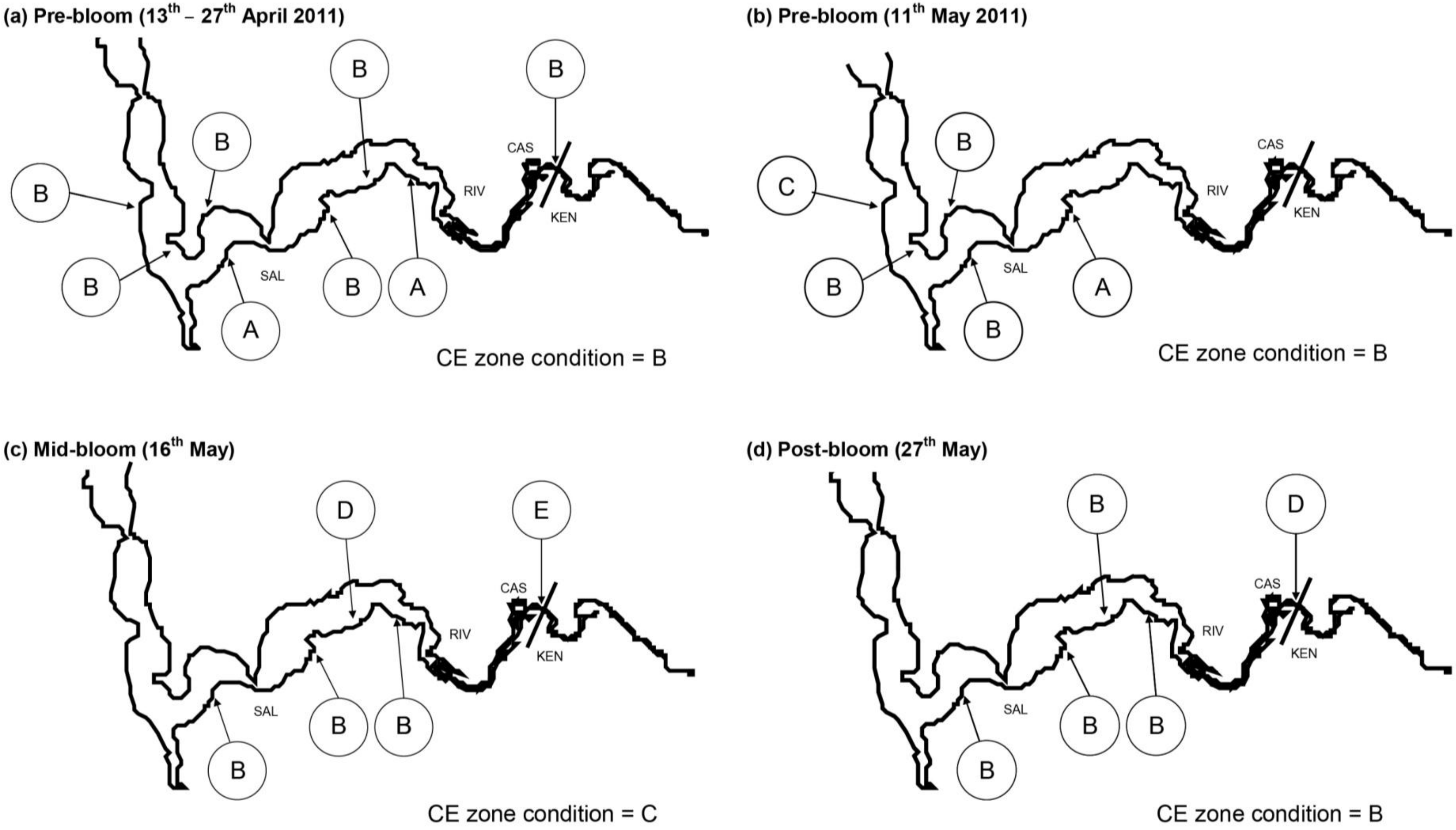


Figure 25. Maps of the Canning Estuary (CE) zone of the Swan-Canning Estuary, illustrating nearshore Fish Community Index condition grades (A-E; derived via the 'unequal-quantile-based grading system' applied to the full historical nearshore data set) for sites sampled before (a, b), during (c) and after (d) a *Karlodinium veneficum* bloom in May 2011. Overall condition grade for the CE zone, based on the mean index score across sites, is also shown.

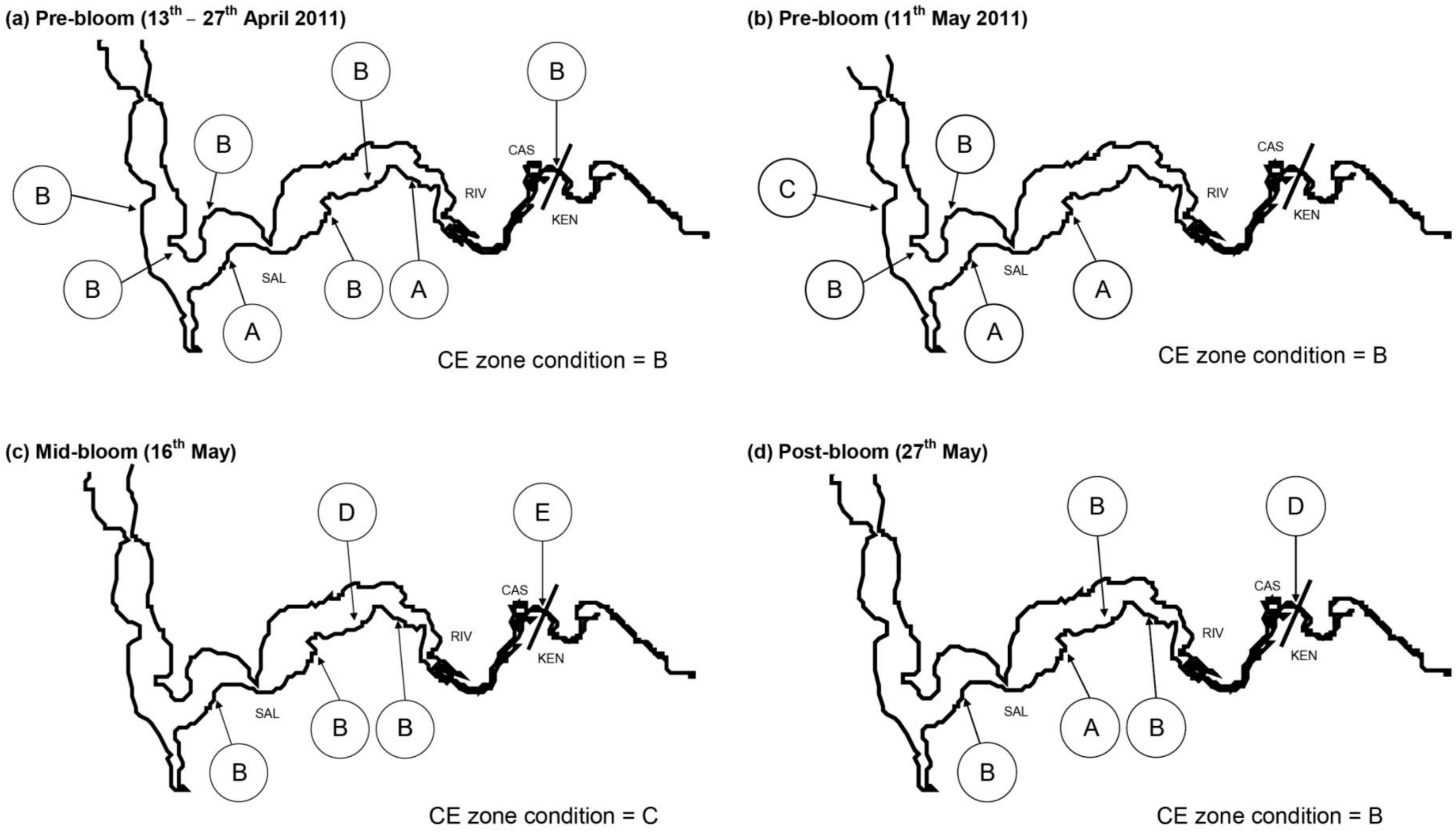


Figure 26. Maps of the Canning Estuary (CE) zone of the Swan-Canning Estuary, illustrating nearshore Fish Community Index condition grades (A-E; derived via the 'unequal-quantile-based grading system' applied to the 21.5 m historical nearshore data set) for sites sampled before (a, b), during (c) and after (d) a *Karlodinium veneficum* bloom in May 2011. Overall condition grade for the CE zone, based on the mean index score across sites, is also shown.

The consistency of condition grades between repeated sampling occasions separated by several weeks has been noted above for the case of the CE zone in April-May 2011, and is indicative of a good degree of robustness to the effects of natural variability. Again, the ecological condition grades awarded to each zone were also relatively consistent across repeated sampling occasions within and between seasons in 2011-12. The unequal quantile systems based on the full and 21.5 m historical data sets both returned very similar grades in most instances, with the slightly greater conservatism of the former evident in the C grades characterizing the ecological condition of the estuary as a whole during 2011 (Table 10). It is again notable that both grading systems identified particularly low ecological condition (grade D) for the nearshore waters of the USE in May 2011 and in summer 2012, reflecting the algal blooms that affected this zone during these periods (Table 6 & 10).

Table 10. Nearshore condition grades (A-E, as determined under the unequal quantile-based grading system using each historical data set) for zones of the Swan-Canning Estuary during repeated sampling occasions in 2011 and 2012.

Estuary Zone	*Full historical data set*						*21.5 m historical data set*					
	Su 2011		**Au 2011**		**Su 2012**	**Au 2012**	**Su 2011**		**Au 2011**		**Su 2012**	**Au 2012**
	Mth 1	Mth 2	Mth 1	Mth 2			Mth 1	Mth 2	Mth 1	Mth 2		
LSCE	B	C	B	C	B	C	B	C	B	C	B	D
CE	C	C	B	B	B	B	C	C	B	B	B	B
MSE	C	C	C	B	B	C	C	C	C	B	B	B
USE	B	B	C	D	D	B	B	B	C	D	D	B
Estuary	**C**	**C**	**B**	**C**	**B**	**B**	**B**	**B**	**B**	**C**	**B**	**B**

Offshore index:

The offshore grade boundaries determined using the unequal quantile-based grading system again differed markedly from those of the other classification/grading schemes. This was most notable in the case of the lowest grade boundary, with the E grade being defined by scores of less than *ca.* 37 points (Fig. 27, Table 11); considerably higher than the boundary score of <25 for very poor condition under the provisional scheme yet lower than the equivalent boundary under the equal quintile-based system. The grade boundaries for the offshore index were, however, again notably lower than their nearshore equivalents (*cf.* Tables 9 and 11), reflecting the lower index scores that have historically been observed for samples taken from deeper, offshore waters.

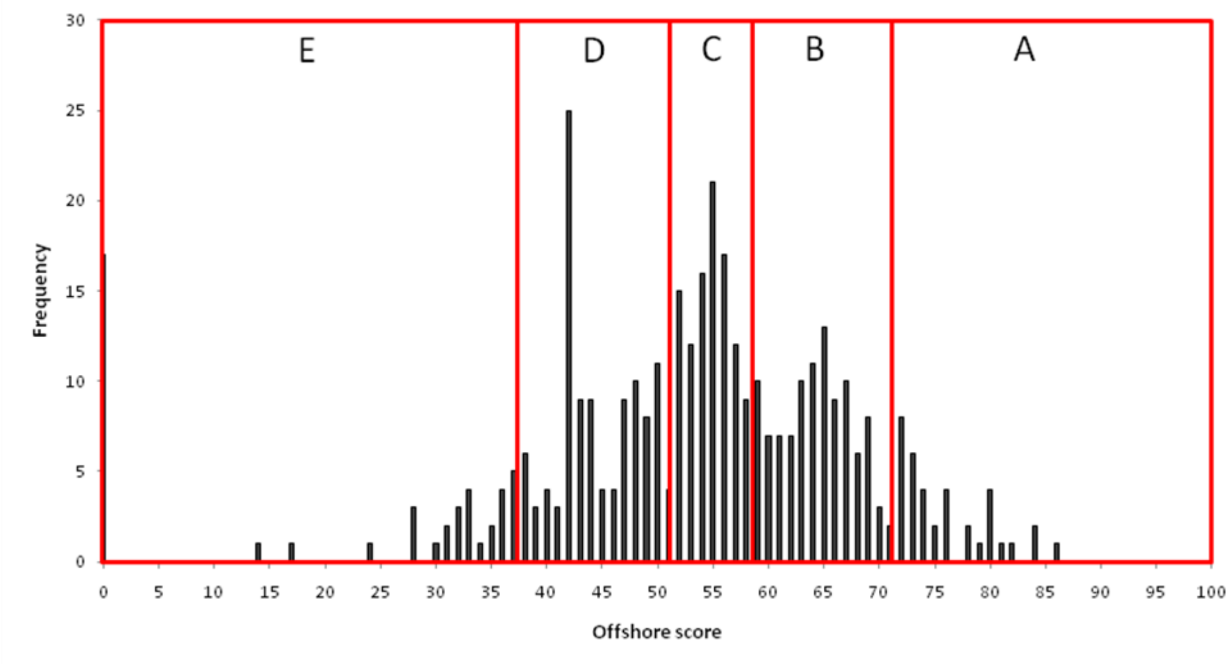


Figure 27. Frequency distribution of offshore Fish Community Index scores from all samples collected between 1977 and 2009 in the Swan-Canning Estuary (full historical data set). Boundaries for ecological condition grades A-E, determined under the unequal quantile-based grading system, are shown in red.

Table 11. Fish Community Index scores comprising each of the five condition grades for offshore waters, as defined using an unequal quantile-based grading system based on the full historical offshore data set. The percentage of samples in the 2011-12 validation data set (*n* = 146) awarded each grade is also shown.

Condition grade	Scores	Validation %
A	>70.7	13.0
B	58.4-70.7	41.1
C	50.6-58.4	21.2
D	36.8-50.6	23.3
E	<36.8	1.4

The ranges of scores representing each of the intermediate grades B, C and D under the unequal quantile-based grading systems were broader than those under the equal quintile-based system (Fig. 27). As a result, the unequal quantile-based grading system is likely to be more robust to the effects of natural variability. This scheme also provides a more conservative grading at the higher end of the ecological condition scale, with only 13% of samples in the validation data set receiving the A grade (Table 11), compared to 25% under the equal quintile approach (Table 7).

The greater conservatism of this scheme is also evident at the zonal scale, with no A grades being awarded for the offshore waters in any zone during 2011-12 (Table 12). The grades awarded to offshore waters under the unequal quantile system were also more consistent across repeated sampling occasions than were those derived using the equal quintile-based system (*cf.* Tables 8 and 12), reflecting the greater robustness of the former approach. Despite the conservatism and robustness of this approach, it retains the sensitivity to identify and communicate poor ecological condition, with the offshore waters of several zones straddling the D-grade boundary on numerous occasions during 2011-12.

Table 12. Offshore condition grades (A-E, as determined under the unequal quantile-based grading system using the historical data set) for zones of the Swan-Canning Estuary during repeated sampling occasions in 2011 and 2012.

	Full historical data set					
Estuary Zone	**Su 2011**		**Au 2011**		**Su 2012**	**Au 2012**
	Mth 1	Mth 2	Mth 1	Mth 2		
LSCE	B	B	B	C	B	B
CE	C	D/C	C	C	C/D	C
MSE	B	B	C/D	C/B	B	B
USE	B	B	B	C/D	B	C/B
Estuary	**B**	**B**	**C**	**C**	**B**	**B**

4.4. Conclusions – evaluation of optimal grading system

Ecological indicators ideally should exhibit both the sensitivity to detect and communicate ecosystem responses to measurable stressors or perturbations and the robustness to avoid erratic oscillations in assessment grades as a result of natural variability in the composition of biological populations. In the absence of independent ecological measures (*e.g.* other quantitative indices) against which to set them, the scoring thresholds between condition grades/classes should be established via an approach which seeks to optimise both the sensitivity and robustness of the resulting indices. We sought therefore to identify the optimal grading system for the Fish Community Indices based on the apparent sensitivity, consistency and utility of index outputs under each of the proposed alternatives to the provisional descriptive classification scheme, using a data set for validation that was independent from that used to define the grade boundaries.

The distribution test classification system is not considered to be a favourable alternative to the provisional scheme. It offers relatively little resolution of the ecological condition of the estuary, is not particularly informative as a means of communicating with the public and deviates from the alphanumeric grading systems proposed for other component indices of future report cards for the Riverpark. Moreover, the assumptions and limitations of the statistical tests on which it is based limit its utility for assessing and reporting ecological condition.

In contrast, the percentile-based grading systems provide alphanumeric outputs which are consistent with the needs of proposed report cards and are likely to be easily understood by the public and a broad range of stakeholders. The five grades employed under these systems offer greater potential resolution of spatial and temporal differences in ecological condition than those approaches using four grades or classes. Moreover, an odd number of grades reduces the likelihood of a grade boundary straddling the mean /median observed score, increasing the robustness of the index.

The unequal quintile-based approaches were characterised by broader scoring ranges representing the central B-D grades and by more conservative grade boundaries for higher condition grades, relative to the equal quintile-based schemes. As a result, the former approaches are more robust and, whilst possessing sufficient sensitivity to identify and communicate instances of particularly low or high ecological condition, also provide a somewhat precautionary assessment (*i.e.* fewer A or E grades) that minimises the likelihood of excessively optimistic or pessimistic assessments of estuarine condition.

Use of the full historical data sets in these percentile-based approaches generated communication outputs which were slightly more consistent and conservative than did those restricted to the 21.5 m data set, yet which were sensitive enough to identify instances of declining ecological condition due to the effects of algal blooms. Moreover, the use of full historical data sets ensures consistency with the data sets previously used to select metrics and establish reference conditions, and is thus considered to be preferable.

Overall, the alphanumeric grading system based on unequal quantiles of the distribution of scores in the full historical data set provides the most robust yet sensitive grading scheme and is thus proposed as the optimal approach for future implementation of both the offshore and nearshore indices.

5. Development of a monitoring regime for the Swan-Canning Riverpark

5.1. Summary evaluation of progress to date

The process of developing and validating these fish-based multimetric indices has spanned five years and represents the culmination of many detailed and technical scientific analyses. The validation of these indices, which commenced during the previous scoping and development project, has been completed in the course of the current study, and they have now been shown to meet all of the criteria on which successful and useful indicators are judged (Table 13).

Table 13. Re-evaluation of the nearshore and offshore multimetric Fish Community Indices developed for the Swan-Canning Estuary (see Hallett 2010, Valesini et al. 2011, Hallett et al. 2012b for more details). Issues that have been addressed in the course of the current study are emboldened.

Criterion	***Evaluation***	
Objective	✓	The indices were developed, and designed to be implemented, using objective procedures with a minimal input of subjective judgement.
Rigorous	✓	The rationale behind the indices has been clearly defined and they are conceptually well understood (see Fig. 1). They are measurable in both quantitative (scores of 0-100) and qualitative (condition grades A-E) terms. Index development has employed widely accepted approaches, assumptions and techniques. Where novel methodologies were required, these were developed and applied with a focus on statistical rigour, and subjected to scientific peer-review (*e.g.* Hallett et al. 2012b).
Robust	✓	Various steps to minimise the influence of 'noise' (replicate to replicate variability) and natural or sampling differences were taken throughout index development. This included eliminating erratically variable metrics, accounting for natural spatial and temporal influences on fish metric values, and standardising the data for methodological biases. This ensures that the resulting indices are able to detect the effects of anthropogenic changes against a background of natural and/or sampling-related variability. Validation of the indices has shown that that grading of the condition of the estuary was robust and reliable when the above effects were accounted for.
Repeatable	✓	The indices were designed to be straightforward, repeatable and inexpensive to measure, analyse and interpret, requiring expert input only for the correct identification of captured fish species. Repeatability of the index has been ensured by the development of a

Criterion		*Evaluation*
		clear set of standard protocols (see section 5.2) which are easily understood by any person with general scientific knowledge. More broadly, the approach and techniques for developing these indices could easily be modified for application to other estuaries across the south-west bioregion.
Sensitive	✓	The consistent decrease observed in offshore index scores over the last three decades strongly suggests that this index is capable of detecting the widely-perceived, long-term decline in the condition of the offshore waters of the Swan-Canning Estuary. **Moreover, the sensitivity of these indices to relatively short, localised environmental perturbations (*i.e.* algal blooms) related to human-caused stressors, has now been demonstrated, in terms of both historical and contemporary events.**
Consistent	✓	Validation has demonstrated that estuarine condition grades were not unduly affected by random sampling variability or by natural, inter-seasonal variability. **In addition, the consistency of both nearshore and offshore index scores between repeated sampling occasions within the same season has now been demonstrated, and power analyses have been conducted to determine the appropriate level of sampling intensity. The results of these investigations have informed the design of a suitable future monitoring regime (section 5.2).**
Communicable	✓	Index outputs can be communicated quantitatively (0-100) and qualitatively (grades A-E) and thus are simply and easily understood by managers and the public alike. Index scores may be calculated for the system as a whole on an annual basis, or for individual ecological management zones and/or seasons.

Despite the complexity of the process by which these indices have been **developed**, it must again be emphasised that their future **implementation** and use for assessing the ecological condition of the Swan-Canning Estuary is, in contrast, conceptually simple and technically straightforward. The process by which these indices should be implemented and used is summarised as a series of steps in the lower (red) portion of Fig. 28.

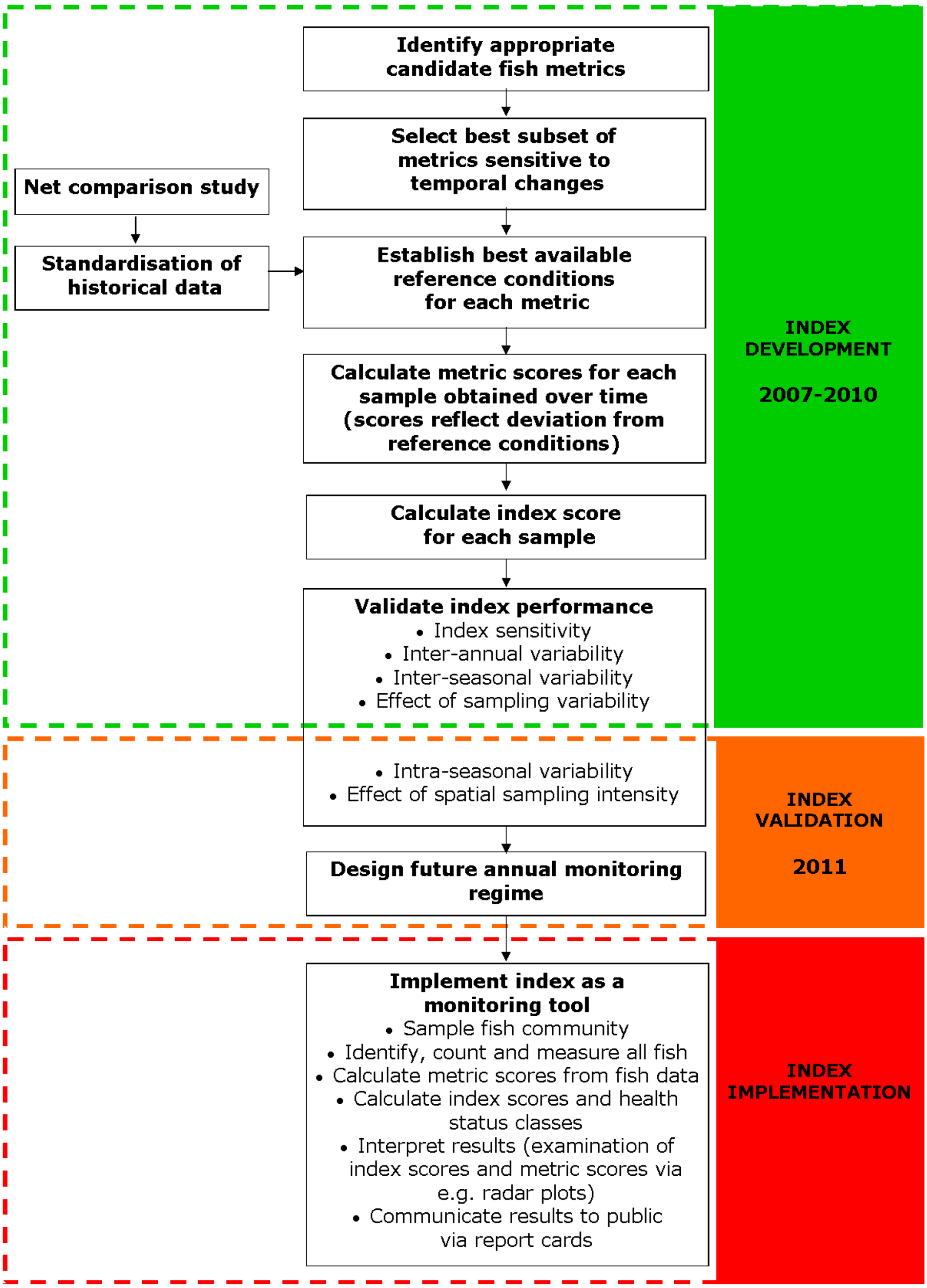


Figure 28. Summary of the stages in the development, validation and implementation of multimetric Fish Community Indices for the Swan-Canning Estuary.

5.2. Proposed monitoring regime for the Swan-Canning Riverpark

This section of the report incorporates the findings and lessons arising from the comprehensive process of index development, validation and review, and describes a rigorous, practicable and cost-effective monitoring regime for the future implementation of these indices as a management and communication tool. It provides a detailed account of each of the steps in the process of index implementation, from the sampling design and collection of data, via metric and index calculation, to the presentation, interpretation and communication of index results (for more background detail please see Hallett 2010, Valesini et al. 2011).

5.2.1. Collecting fish community data

<u>Sampling design</u>

Sampling of the fish communities from the Swan-Canning Estuary should be conducted:

(i) at a minimum spatial sampling intensity of six sites per ecological management zone (Table 14; Fig. 29),

(ii) once in the middle month of both summer and autumn (the seasons in which natural variability in the fish community is typically lowest), to encompass inter-seasonal variability in index scores in any year,

(iii) annually, to encompass natural inter-annual variability in index scores and thus provide a more effective basis for detecting trends and distinguishing signals of anthropogenic degradation affecting the system,

(iv) during daylight hours in nearshore waters (<2 m depth) and at night in offshore waters (>2 m depth), to eliminate the effects on index scores of diel differences in fish community composition.

If the timing of planned sampling coincides with the occurrence of an algal bloom, sampling should ideally be carried out during the bloom and again upon cessation of the bloom, at least within the affected zone(s) and preferably within adjacent zones (dependent on the availability of both funding and sampling days). This will enable the effect of the bloom on the fish community to be quantified, and the condition of the estuary in both bloom-affected and unaffected states to be reported.

Table 14. Descriptions of (a) nearshore and (b) offshore sampling sites under the proposed future monitoring regime.

Zone	Site Code	Lat-Long (S, E)	Description
(a) - *Nearshore*			
LSCE	LSCE3	32°01'29'', 115°46'27''	Shoreline in front of vegetation on eastern side of Point Roe, Mosman Pk
	LSCE4	31°59'26'', 115°47'08''	Grassy shore in front of houses to east of Claremont Jetty
	LSCE5	32°00'24'', 115°46'52''	North side of Point Walter sandbar
	LSCE6	32°01'06'', 115°48'19''	Shore in front of bench on Attadale Reserve
	LSCE7	32°00'11'', 115°50'29''	Sandy bay below Point Heathcote
	LSCE8	31°59'11'', 115°49'40''	Eastern side of Pelican Point, immediately south of sailing club
CE	CE1	32°01'28'', 115°51'16''	Sandy shore to south of Deepwater Point boat ramp
	CE2	32°01'54'', 115°51'33''	Sandy beach immediately to north of Mount Henry Bridge
	CE5	32°01'40'', 115°52'58''	Bay in Shelley Beach, adjacent to jetty
	CE6	32°01'29'', 115°53'11''	Small clearing in vegetation off North Riverton Drive
	CE7	32°01'18'', 115°53'43''	Sandy bay in front of bench, east of Wadjup Point
	CE8	32°01'16'', 115°55'14''	Sandy beach immediately downstream of Kent Street Weir
MSE	MSE2	31°58'12'', 115°51'07''	Sandy beach on South Perth foreshore, west of Mends St Jetty
	MSE4	31°56'34'', 115°53'06''	Shoreline in front of Belmont racecourse, north of Windan Bridge
	MSE5	31°56'13'', 115°53'23''	Beach to west of jetty in front of Maylands Yacht Club
	MSE6	31°57'13'', 115°53'56''	Small beach upstream of Belmont Water Ski Area boat ramp
	MSE7	31°55'53'', 115°55'10''	Beach in front of scout hut, east of Garratt Road Bridge
	MSE8	31°55'37'', 115°56'18''	Vegetated shoreline, Claughton Reserve, upstream of boat ramp
USE	USE1	31°55'20'', 115°57'03''	Small beach adjacent to jetty at Sandy Beach Reserve, Bassendean
	USE3	31°53'43'', 115°57'32''	Sandy bay opposite Bennett Brook, at Fishmarket Reserve, Guildford
	USE4	31°53'28'', 115°58'32''	Shoreline in front of Guildford Grammar stables, opposite Lilac Hill Park
	USE5	31°53'13'', 115°59'29''	Small, rocky beach after bend in river at Ray Marshall Park
	USE6	31°52'41'', 115°59'31''	Small beach with iron fence, in front of Caversham house
	USE7	31°52'22'', 115°59'39''	Sandy shore on bend in river, below house on hill, upstream of powerlines
(b) – *Offshore*			
LSCE	LSCE1G	32°00'24'', 115°46'56''	In deeper water *ca* 100 m off north side of Point Walter sandbar
	LSCE2G	32°00'12'', 115°48'07''	Alongside seawall west of Armstrong Spit, Dalkeith
	LSCE3G	32°01'00'', 115°48'44''	Parallel to shoreline, running westwards from Beacon 45, Attadale
	LSCE4G	32°00'18'', 115°50'01''	In deep water of Waylen Bay, from *ca* 50 m east of Applecross jetty
	LSCE5G	31°59'37'', 115°51'09''	Perpendicular to Como Jetty, running northwards
	LSCE6G	31°59'12'', 115°49'42''	*Ca* 20 m from, and parallel to, sandy shore on east side of Pelican Point
CE	CE1G	32°01'58'', 115°51'36''	Underneath Mount Henry Bridge, parallel to northern shoreline
	CE2G	32°01'48'', 115°51'46''	Parallel to, and *ca* 20 m from, western shoreline of Aquinas Bay
	CE3G	32°01'49'', 115°52'19''	To north of navigation markers, Aquinas Bay
	CE4G	32°01'48'', 115°52'33''	Adjacent to Old Post Line (SW-ern end; Salter Point)
	CE5G	32°01'36'', 115°52'52''	Adjacent to Old Post Line (NE-ern end; Prisoner Point)
	CE6G	32°01'20'', 115°53'15''	Adjacent to Old Post Line, Shelley Water
MSE	MSE1G	31°58'03'', 115°51'03''	From jetty at Point Belches towards Mends St Jetty, Perth Water
	MSE2G	31°56'57'', 115°53'05''	Downstream of Windan Bridge, parallel to Burswood shoreline
	MSE3G	31°56'22'', 115°53'05''	Downstream from port marker, parallel to Joel Terrace, Maylands
	MSE4G	31°57'13'', 115°54'12''	Parallel to shore from former boat shed jetty, Cracknell Park, Belmont
	MSE5G	31°55'57'', 115°55'12''	Parallel to southern shoreline, upstream of Garratt Road Bridge
	MSE6G	31°55'23'', 115°56'25''	Parallel to eastern bank at Garvey Pk, from south of Ron Courtney Island
USE	USE1G	31°55'19'', 115°57'09''	Parallel to tree-lined eastern bank, upstream of Sandy Beach Reserve
	USE2G	31°53'42'', 115°57'40''	Along northern riverbank, running upstream from Bennett Brook
	USE3G	31°53'16'', 115°58'42''	Along northern bank on bend in river, to north of Lilac Hill Park
	USE4G	31°53'17'', 115°59'23''	Along southern bank, downstream from bend at Ray Marshall Pk
	USE5G	31°52'13'', 115°59'40''	Running along northern bank, upstream from Sandalford winery jetty
	USE6G	31°52'13'', 116°00'18''	Along southern shore adjacent to Midland Brickworks, from outflow pipe

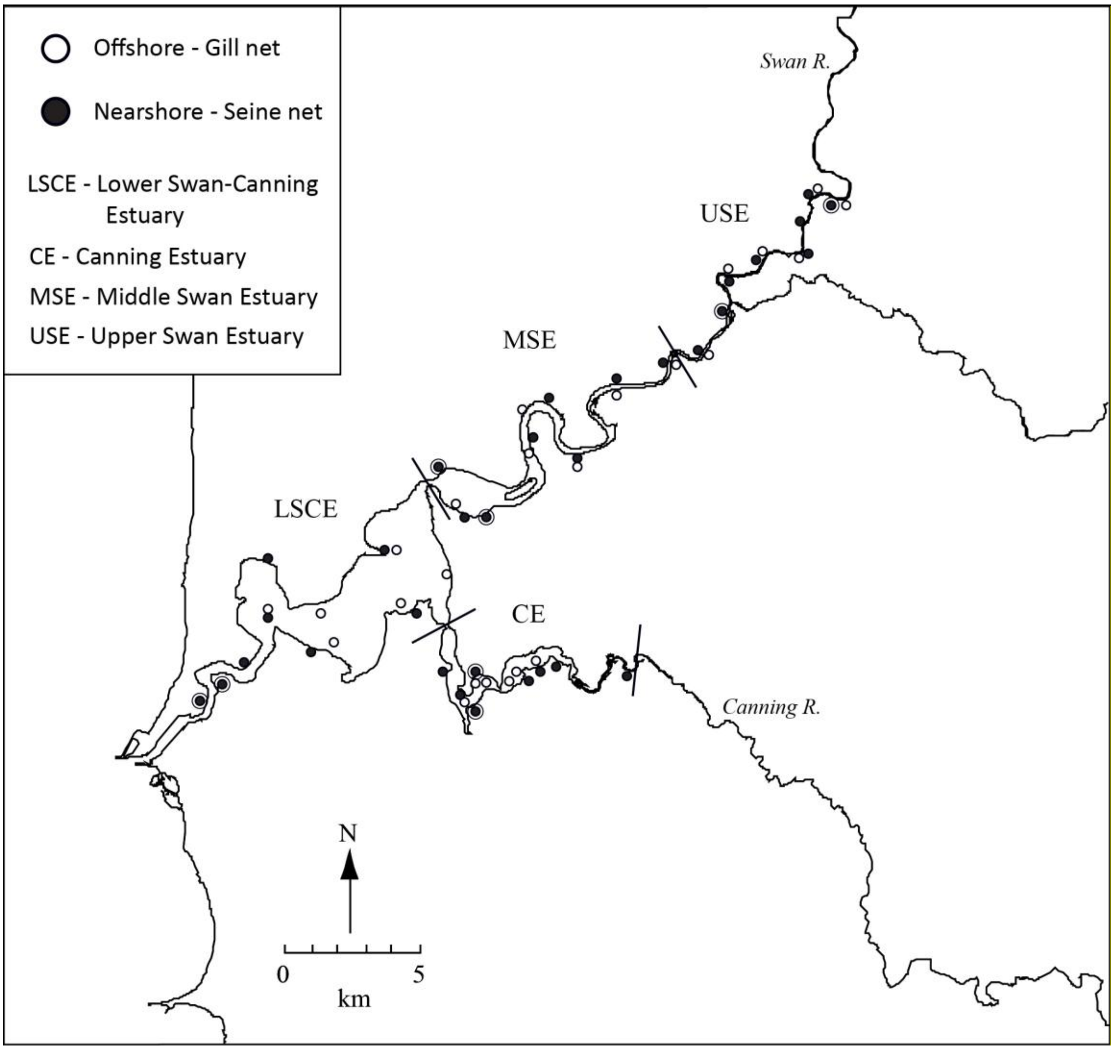


Figure 29. Map of the Swan-Canning Estuary, showing the locations of the six nearshore (<2 m depth) and six offshore (>2 m depth) sites per zone at which fish assemblages should be sampled under a future monitoring regime for the Fish Community Indices (N.B. two potential, additional nearshore sites in each zone are circled).

Nearshore sampling methods

- On each sampling occasion, one replicate sample of the nearshore fish community is collected from each of the fixed, nearshore sampling sites shown in Fig. 29.
- Sampling should not be conducted during or within 3-5 days following any significant flow event.
- Nearshore fish samples are collected using a beach seine net that is 21.5 m long, 1.5 m deep and comprises two 10 m-long wings (6 m of 9 mm mesh and 4 m of 3 mm mesh) and a 1.5 m-long bunt (3 mm mesh).

- This net is walked out from the beach to a maximum depth of approximately 1.5 m and deployed parallel to the shore, and is then rapidly dragged towards and onto the shore, so that it sweeps a roughly semicircular area of approximately 116 m^2.
- If a seine net deployment returns a catch of fewer than five fish, an additional sample is performed at the site (separated from the first sample by either 15 minutes or by 10-20 m distance). In the event that more than five fish are caught in the second sample, this second replicate is then to be used as the sample for that site, and those fish from the first sample returned to the water alive. If, however, 0-5 fish are again caught, the original sample can be assumed to have been representative of the fish community present, and be used as the sample for that site, the fish from the latter sample being returned alive to the water. The above procedure thus helps to identify whether a collected sample is representative of the fish community present, and enables instances of false negative catches to be identified and eliminated.
- Once an appropriate sample has been collected, any fish that may be readily identified to species (*e.g.* those larger species which are caught in relatively lower numbers) are identified, counted and returned to the water alive.
- All other fish caught in the nets are placed into zip-lock polythene bags, euthanized in ice slurry and preserved on ice in eskies in the field, except in cases where large catches (*e.g.* thousands) of small fish are obtained. In such cases, an appropriate sub-sample (*e.g.* one half to one eighth of the entire catch) is retained and the remaining fish are returned alive to the water. All retained fish are then bagged and frozen until their identification in the laboratory.
- The following data associated with each sample should be recorded both on a waterproof label placed into the bag with the retained fish, and on a separate, waterproof field recording sheet:

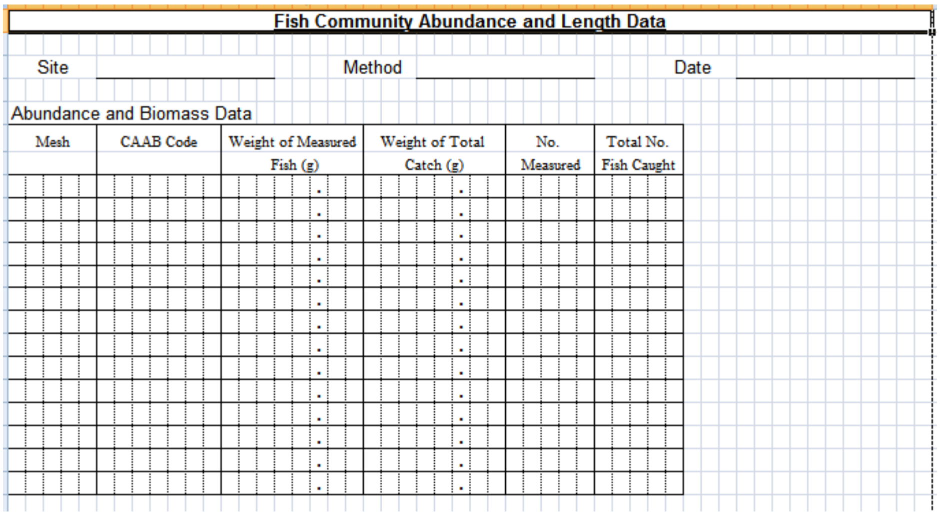
- Sample date
- Sample code (see Table 14a)
- Method of collection (‘21.5 m seine net - nearshore’)
- Species names and abundances of all fish returned from the sample
- Sub-sample fraction retained, if applicable.

Offshore sampling methods

- On each sampling occasion, one replicate sample of the offshore fish community is collected from each of the fixed, offshore sampling sites shown in Fig. 29.
- Sampling should not be conducted within 3-5 days following any significant flow event.
- Offshore fish samples are collected using a sunken, multimesh gill net that consists of eight 20 m-long panels with stretched mesh sizes of 35, 51, 63, 76, 89, 102, 115 and 127 mm. These nets are deployed from a boat immediately before sunset and retrieved after three hours.
- Given the time and labour associated with offshore sampling, and the need to monitor the set nets for safety purposes, a maximum of three such replicate net deployments should be performed within a single zone in any one night. The three nets should be deployed sequentially, and retrieved in the same order.
- During net retrieval (and, typically, when catch rates are sufficiently low to allow fish to be removed rapidly in the course of retrieval), any fishes that may be removed easily from the net are carefully removed, identified, counted, recorded and returned to the water alive as the net is pulled into the boat.
- All other fish caught in the nets are removed once the net has been retrieved. Retained fish are placed into zip-lock polythene bags in ice slurry, preserved on ice in eskies in the field, and subsequently frozen until their identification in the laboratory.
- The following data associated with each sample should be recorded both on a waterproof label placed into the bag with the retained fish, and on a separate, waterproof field recording sheet:

- Sample date
- Sample code (see Table 14b)
- Method of collection (‘gill net - offshore’)
- Species names and abundances of all fish returned from the sample.

Following their identification to the lowest possible taxon in the field or laboratory by fish specialists trained in fish taxonomy, all assigned scientific and common names are checked and standardised by referencing the Checklist of Australian Aquatic Biota (CAAB) database (Rees *et al.* 2006), and the appropriate CAAB species code is allocated to each species. The abundance data for each species in each sample is entered onto the following sample data sheets. (Please note that if these indices are adopted for implementation, data sheet templates and copies of all software required to perform the following calculations will be provided.)



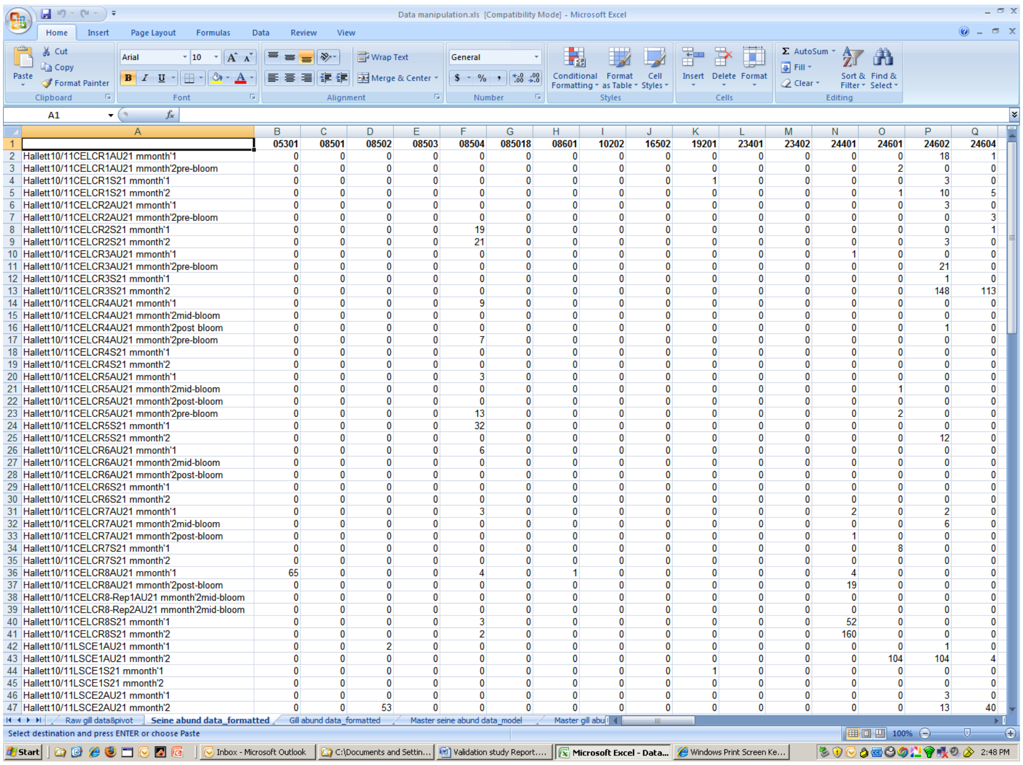
Fish Community Abundance and Length Data

Site ____________ Method ____________ Date ____________

Abundance and Biomass Data

Mesh	CAAB Code	Weight of Measured Fish (g)	Weight of Total Catch (g)	No. Measured	Total No. Fish Caught
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		
		.	.		

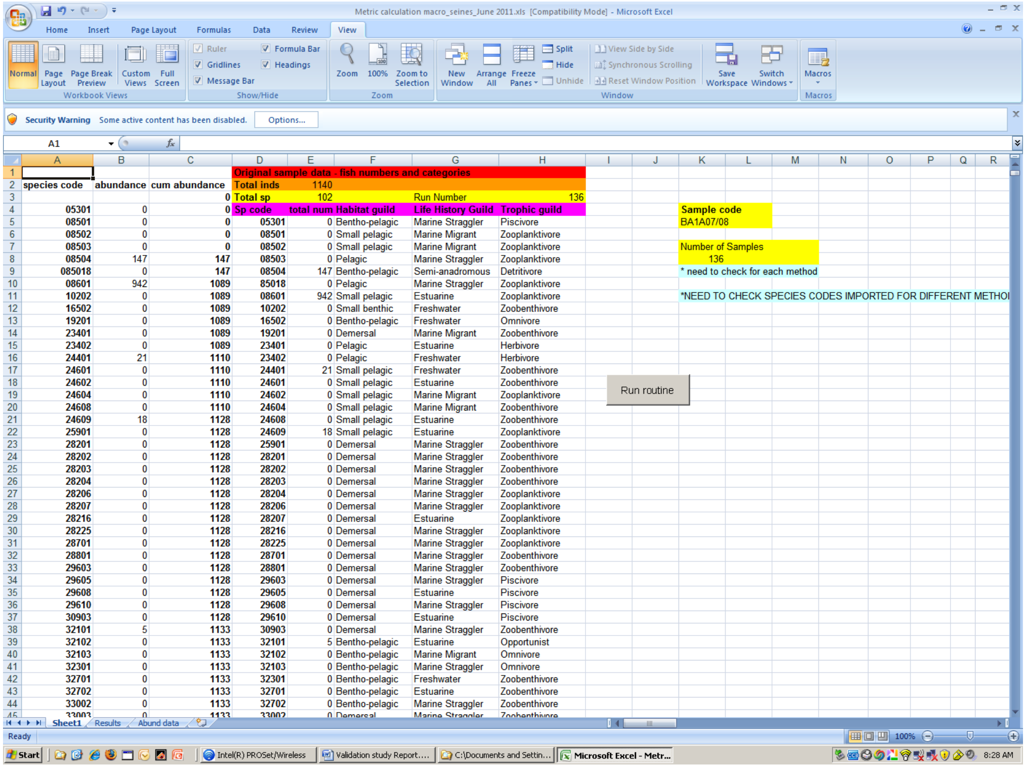
These data are then checked, entered and stored in an Excel spreadsheet, with samples as rows and species codes as columns:

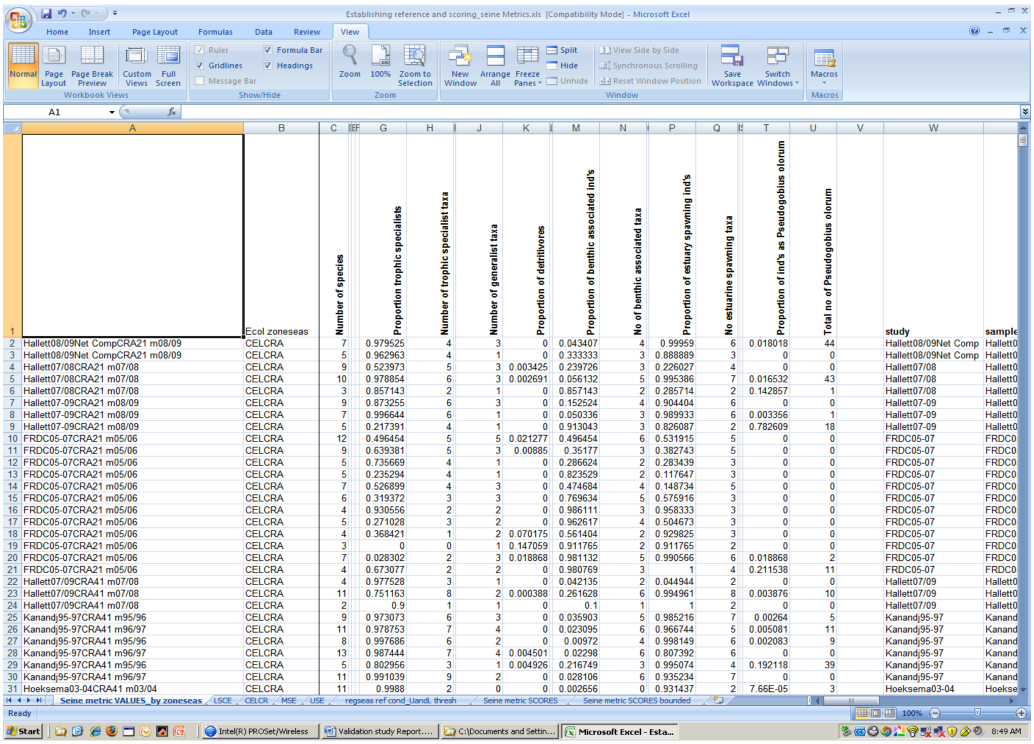


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		05301	08501	08502	08503	08504	085018	08601	10202	16502	19201	23401	23402	24401	24601	24602	24604
2	Hallett10/11CELCR1AU21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	1
3	Hallett10/11CELCR1AU21 mmonth'2pre-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
4	Hallett10/11CELCR1S21 mmonth'1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	0
5	Hallett10/11CELCR1S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	10	5
6	Hallett10/11CELCR2AU21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
7	Hallett10/11CELCR2AU21 mmonth'2pre-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
8	Hallett10/11CELCR2S21 mmonth'1	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	1
9	Hallett10/11CELCR2S21 mmonth'2	0	0	0	0	21	0	0	0	0	0	0	0	0	0	3	0
10	Hallett10/11CELCR3AU21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11	Hallett10/11CELCR3AU21 mmonth'2pre-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0
12	Hallett10/11CELCR3S21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
13	Hallett10/11CELCR3S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	148	113
14	Hallett10/11CELCR4AU21 mmonth'1	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
15	Hallett10/11CELCR4AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Hallett10/11CELCR4AU21 mmonth'2post bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
17	Hallett10/11CELCR4AU21 mmonth'2pre-bloom	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0
18	Hallett10/11CELCR4S21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Hallett10/11CELCR4S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Hallett10/11CELCR5AU21 mmonth'1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
21	Hallett10/11CELCR5AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
22	Hallett10/11CELCR5AU21 mmonth'2post-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Hallett10/11CELCR5AU21 mmonth'2pre-bloom	0	0	0	0	13	0	0	0	0	0	0	0	0	2	0	0
24	Hallett10/11CELCR5S21 mmonth'1	0	0	0	0	32	0	0	0	0	0	0	0	0	0	0	0
25	Hallett10/11CELCR5S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0
26	Hallett10/11CELCR6AU21 mmonth'1	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
27	Hallett10/11CELCR6AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Hallett10/11CELCR6AU21 mmonth'2post-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	Hallett10/11CELCR6S21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Hallett10/11CELCR6S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Hallett10/11CELCR7AU21 mmonth'1	0	0	0	0	3	0	0	0	0	0	0	0	2	0	2	0
32	Hallett10/11CELCR7AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
33	Hallett10/11CELCR7AU21 mmonth'2post-bloom	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
34	Hallett10/11CELCR7S21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
35	Hallett10/11CELCR7S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Hallett10/11CELCR8AU21 mmonth'1	65	0	0	0	4	0	1	0	0	0	0	0	4	0	0	0
37	Hallett10/11CELCR8AU21 mmonth'2post-bloom	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0
38	Hallett10/11CELCR8-Rep1AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Hallett10/11CELCR8-Rep2AU21 mmonth'2mid-bloom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	Hallett10/11CELCR8S21 mmonth'1	0	0	0	0	3	0	0	0	0	0	0	0	52	0	0	0
41	Hallett10/11CELCR8S21 mmonth'2	0	0	0	0	2	0	0	0	0	0	0	0	160	0	0	0
42	Hallett10/11LSCE1AU21 mmonth'1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0
43	Hallett10/11LSCE1AU21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	104	104	4
44	Hallett10/11LSCE1S21 mmonth'1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
45	Hallett10/11LSCE1S21 mmonth'2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Hallett10/11LSCE2AU21 mmonth'1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
47	Hallett10/11LSCE2AU21 mmonth'2	0	0	53	0	0	0	0	0	0	0	0	0	0	0	13	40

5.2.2. Calculating metric scores from fish data

Values for each fish metric relevant to nearshore or offshore waters are calculated for each sample from the fish species abundance data, based on their guild allocations, using an Excel macro written for the purpose:





5.2.3. Calculating index scores and condition grades

Values for each of the fish metrics in each sample are then converted to bounded scores (0-10), based on the deviation of the observed metric value from the upper and lower threshold values of its appropriate season- and zone-specific reference condition. So, for negative metrics (*i.e.* those whose scores are predicted to decrease in response to increasing degradation –

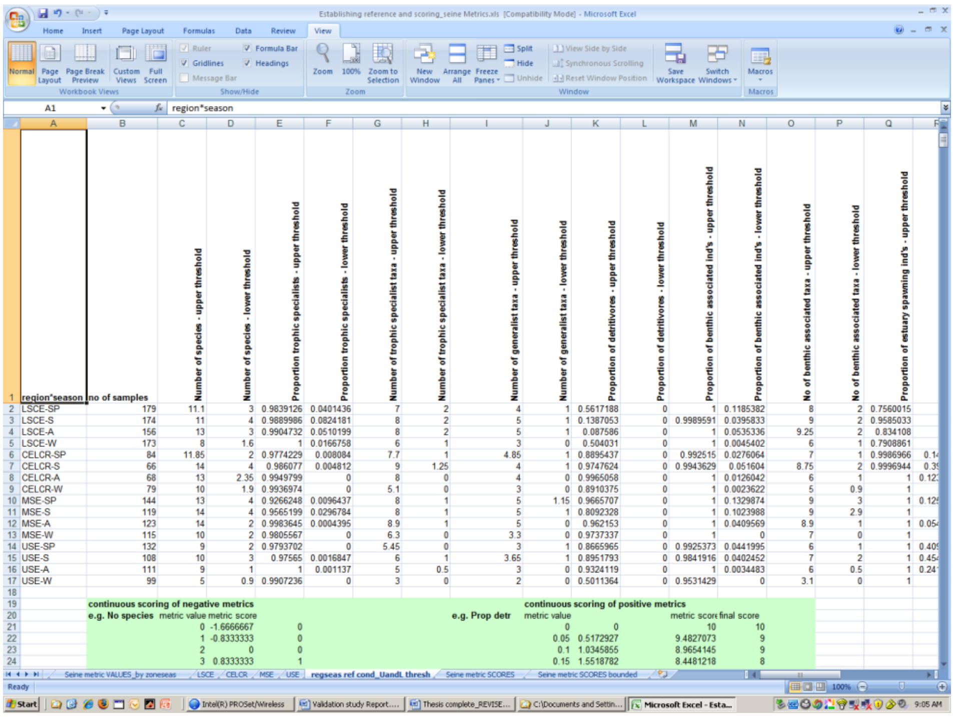
Number of species, Shannon-Weiner diversity, Proportion of trophic specialists, Number of trophic specialist species, Proportion of benthic associated individuals, Number of benthic associated species, Proportion of estuarine spawning individuals, Number of estuarine spawning species), scores are calculated as:

$$Metric\ score = \frac{(Observed\ metric\ value - Lower\ threshold)}{(Upper\ threshold\ - Lower\ threshold)} \times 10$$

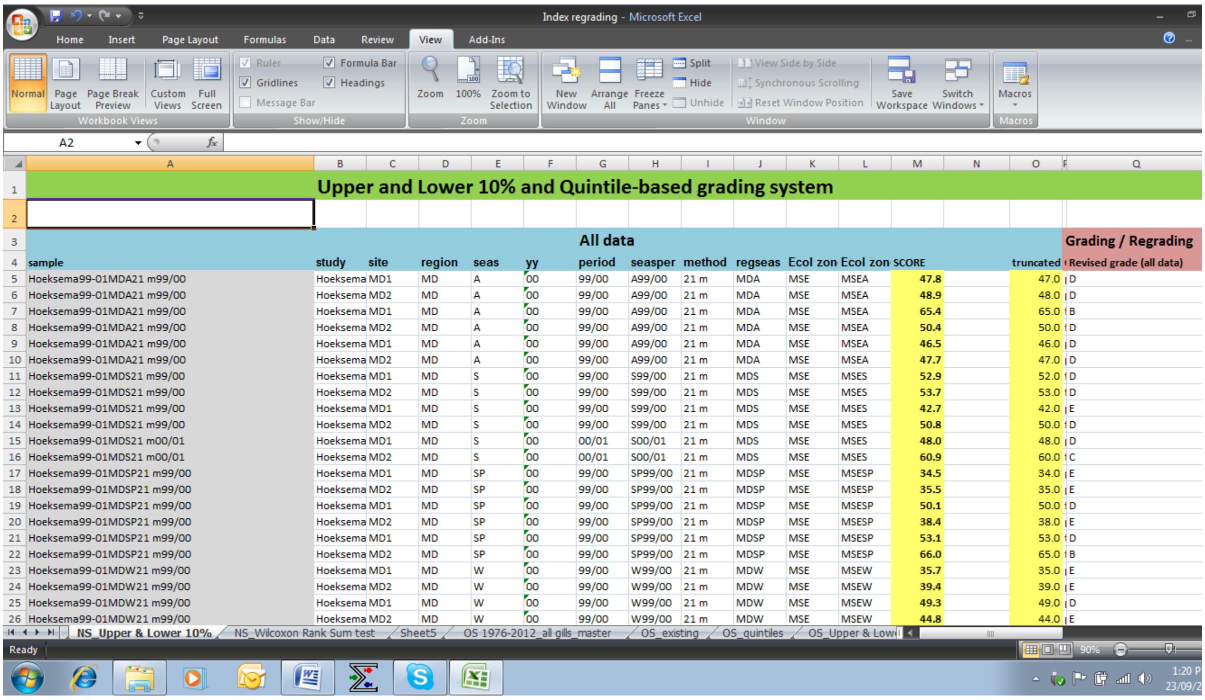
For the remaining, positive metrics (whose scores increase in response to ecological degradation), scores are calculated as:

$$Metric\ score = \left(1 - \frac{(Observed\ metric\ value - Lower\ threshold)}{(Upper\ threshold\ - Lower\ threshold)}\right) \times 10$$

In cases where metric values exceed the upper threshold (*i.e.* outliers), a metric score of 10 is allocated. Moreover, when no fish are caught in a sample, all metrics receive a score of zero:



The bounded scores for each metric are then summed and used to calculate an index score (0-100) for the sample. This score, in turn, defines the condition grade assigned to the sample, in line with the scoring thresholds set out for the nearshore and offshore indices (Table 15):



Upper and Lower 10% and Quintile-based grading system

sample	study	site	region	seas	yy	period	seasper	method	regseas	Ecol zon	Ecol zon	SCORE	truncated	Revised grade (all data)
Hoeksema99-01MDA21 m99/00	Hoeksema	MD1	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	47.8	47.0	D
Hoeksema99-01MDA21 m99/00	Hoeksema	MD2	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	48.9	48.0	D
Hoeksema99-01MDA21 m99/00	Hoeksema	MD1	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	65.4	65.0	B
Hoeksema99-01MDA21 m99/00	Hoeksema	MD2	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	50.4	50.0	D
Hoeksema99-01MDA21 m99/00	Hoeksema	MD1	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	46.5	46.0	D
Hoeksema99-01MDA21 m99/00	Hoeksema	MD2	MD	A	00	99/00	A99/00	21 m	MDA	MSE	MSEA	47.7	47.0	D
Hoeksema99-01MDS21 m99/00	Hoeksema	MD1	MD	S	00	99/00	S99/00	21 m	MDS	MSE	MSES	52.9	52.0	D
Hoeksema99-01MDS21 m99/00	Hoeksema	MD2	MD	S	00	99/00	S99/00	21 m	MDS	MSE	MSES	53.7	53.0	D
Hoeksema99-01MDS21 m99/00	Hoeksema	MD1	MD	S	00	99/00	S99/00	21 m	MDS	MSE	MSES	42.7	42.0	E
Hoeksema99-01MDS21 m99/00	Hoeksema	MD2	MD	S	00	99/00	S99/00	21 m	MDS	MSE	MSES	50.8	50.0	D
Hoeksema99-01MDS21 m00/01	Hoeksema	MD1	MD	S	00	00/01	S00/01	21 m	MDS	MSE	MSES	48.0	48.0	D
Hoeksema99-01MDS21 m00/01	Hoeksema	MD2	MD	S	00	00/01	S00/01	21 m	MDS	MSE	MSES	60.9	60.0	C
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD1	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	34.5	34.0	E
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD2	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	35.5	35.0	E
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD1	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	50.1	50.0	D
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD2	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	38.4	38.0	E
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD1	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	53.1	53.0	D
Hoeksema99-01MDSP21 m99/00	Hoeksema	MD2	MD	SP	00	99/00	SP99/00	21 m	MDSP	MSE	MSESP	66.0	65.0	B
Hoeksema99-01MDW21 m99/00	Hoeksema	MD1	MD	W	00	99/00	W99/00	21 m	MDW	MSE	MSEW	35.7	35.0	E
Hoeksema99-01MDW21 m99/00	Hoeksema	MD2	MD	W	00	99/00	W99/00	21 m	MDW	MSE	MSEW	39.4	39.0	E
Hoeksema99-01MDW21 m99/00	Hoeksema	MD1	MD	W	00	99/00	W99/00	21 m	MDW	MSE	MSEW	49.3	49.0	D
Hoeksema99-01MDW21 m99/00	Hoeksema	MD2	MD	W	00	99/00	W99/00	21 m	MDW	MSE	MSEW	44.8	44.0	E

Table 15. Fish Community Index scores comprising each of the five condition grades for both nearshore and offshore waters.

Condition grade	Nearshore index scores	Offshore index scores
A (very good)	>74.5	>70.7
B (good)	64.6-74.5	58.4-70.7
C (fair)	57.1-64.6	50.6-58.4
D (poor)	45.5-57.1	36.8-50.6
E (very poor)	<45.5	<36.8

5.2.4. Presenting, interpreting and communicating results

The nearshore and offshore Fish Community Indices provide a key tool for surveillance monitoring of the condition of the Swan-Canning Estuary and of each of its component ecological management zones. Surveillance monitoring aims to assess and track long-term and/or broad-scale changes in ecosystem condition (Hering et al. 2010) and enables the reporting and communication of patterns and trends in ecosystem condition to the public and other stakeholders. Such reporting is an essential component of the adaptive management framework, as trends in ecological condition indices provide a quantitative measure of the success of management actions. The ways in which indicator results are presented, communicated, interpreted and acted upon will thus in part determine the success and value of these monitoring and management programs.

Assessment, mapping and trending of estuarine condition

The reporting and communication of results from the Fish Community Index monitoring program should include mean index scores (0-100) along with a measure of their variability (*e.g.* standard error of the mean), and the accompanying condition grades (A-E), both of which may be incorporated into estuarine report cards (*e.g.* see http://eco-check.org/reportcard/Chesapeake/2010/ and Fig. 31). Moreover, the condition of the Swan-Canning Estuary as a whole should be considered and reported alongside that of its individual ecological management zones.

The proximity of the mean index score to grade boundaries should be considered when determining condition grades. It is proposed that mean scores within one point of a grade boundary should be allocated an intermediate grade, denoted using a symbol such as '/', '+' or '-'. For example, a mean nearshore score within one point **over** the boundary score of 64.6 between grades B and C might be denoted 'B/C' or 'B-', whereas if the mean score were within one point **below** the same boundary score, the resulting condition grade might be denoted 'C/B' or 'C+'.

The reporting of ecosystem condition using these indices should follow international best practice and include a combination of synopses and summaries (*e.g.* http://eco-check.org/reportcard/Chesapeake/2010/overview/#_Synopsis), spatial mapping (*e.g.* http://eco-check.org/reportcard/Chesapeake/2010/overview/#_Health_Index_Map), and temporal trending (*e.g.* http://eco-check.org/reportcard/Chesapeake/2010/overview/#_Trends).

Spatial mapping of index results enables the comparison of ecosystem condition between ecological management zones, and thus enables managers to determine which zones of the estuary may be most in need of management intervention. An example of this is illustrated in Fig. 30, whereby spatial mapping highlights the comparatively low ecological condition of the CE and USE zones in summer and autumn of 2007.

These indices also provide a method for tracking the condition of the system over time (*e.g.* as presented in Fig. 31). If negative trends in estuary condition over time exceed manager-defined limits of acceptable change, monitoring results could then be acted upon, for example via the implementation of restoration measures to improve ecosystem condition. Similarly, trends in ecological condition may also be presented for individual zones (*e.g.* as in Fig. 32).

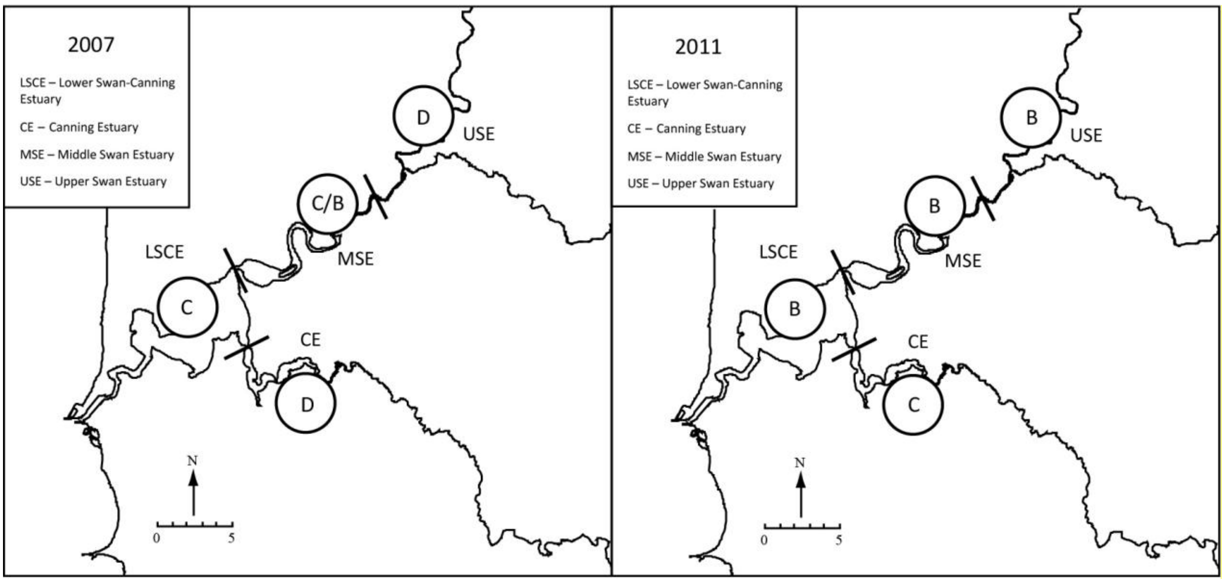


Figure 30. Example maps showing the offshore condition grades for each of the management zones of the Swan-Canning Estuary in 2007 (left) and 2011 (right). Condition grades were determined from the mean offshore Fish Community Index scores recorded from summer and autumn samples in each year, and based on the grading thresholds established using the unequal quantile approach on the full historical data set.

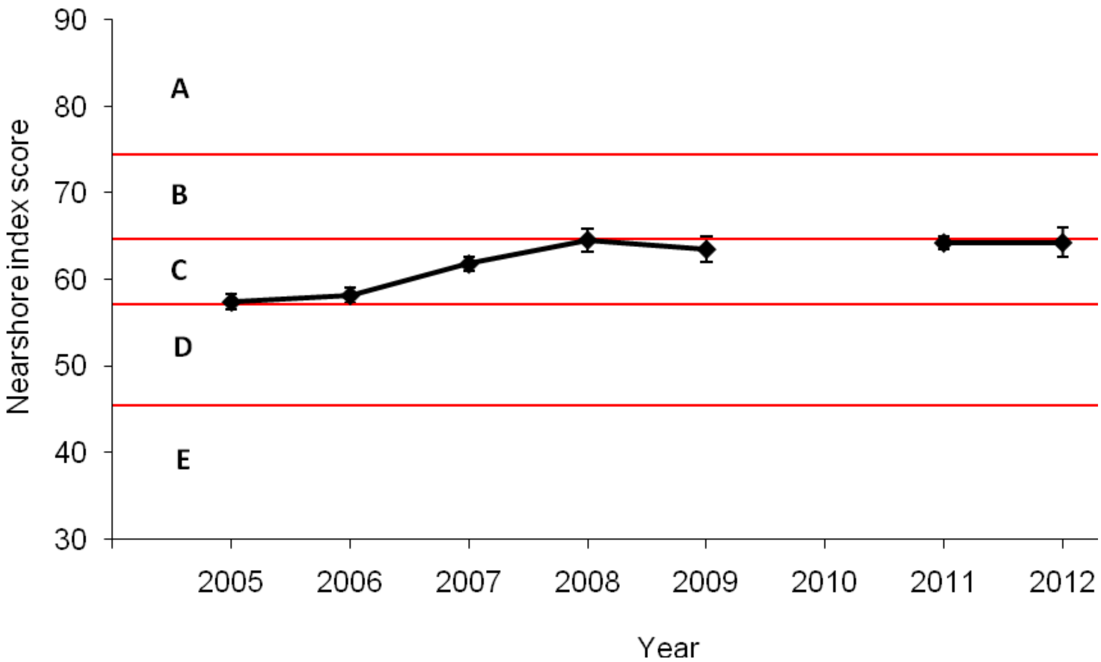


Figure 31. Example trend plot of mean nearshore index scores (+/- standard error) recorded from summer and/or autumn samples across all sites throughout the Swan-Canning Estuary between 2005 and 2012.

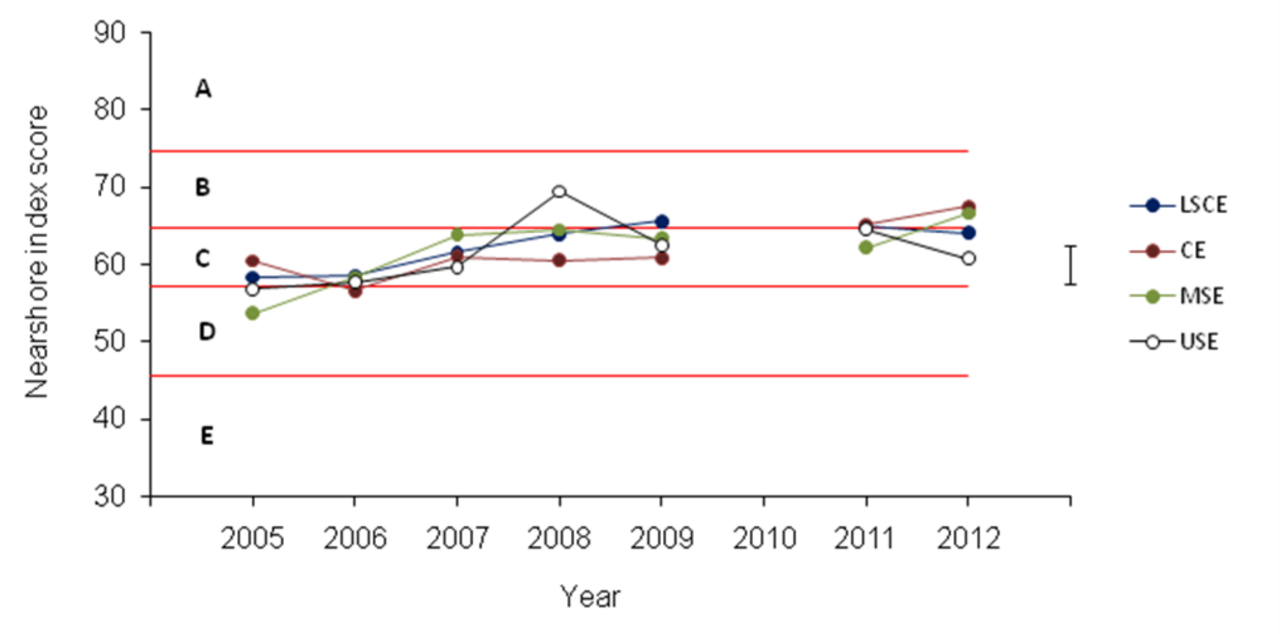


Figure 32. Example trend plot of mean nearshore index scores recorded from summer and/or autumn samples in each zone of the Swan-Canning Estuary between 2005 and 2012. (The average standard error of the means is plotted for clarity).

Analysing and interpreting results

Index results should not only be presented, but also interpreted and acted upon, in order to realise the potential of the indices as tools for adaptive management and community engagement. Consistent and positive long-term trends in index scores provide evidence that management actions are effective in maintaining ecological integrity. In contrast, consistent negative trends in index scores should be taken as evidence that action is needed to alleviate or mitigate human stressors acting on the system.

If potential problems are identified from index results (*i.e.* a severe and/or chronic decline in the condition of certain zones is noted), investigative monitoring (Hering et al. 2010) should be implemented to identify the causal stressors associated with these problems, and thus allow appropriate remedial actions to be implemented.

On a basic level, the interpretation of index results is straightforward and conceptually simple, as outlined in the following scenarios.

(i) If both nearshore and offshore indices increase concomitantly across the entire system, it would suggest an increase in the ecological condition of the estuary as a whole.

(ii) If both indices decreased consistently, it would suggest a decline in overall condition, and would, for example, potentially signal that a threshold of ecological quality has been crossed and that fish were dying and/or leaving the system.

(iii) If, as in the case of the 2004 *Karlodinium veneficum* bloom (Figs. 14 and 15), one index increases whilst the other decreases, this provides evidence of a locational shift in the fish community and supplies valuable information on the relative condition of the nearshore and offshore waters.

At a more detailed level of investigation, one can use radar plots to identify those metrics which are most responsible for driving index scores in time and space, thus helping to determine the specific stressors to which these metrics, and the index, may be responding. For example, the radar plot in Fig. 33 highlights the changes in metric scores which accompanied the onset of the *K. veneficum* bloom in the CE in May 2011, and the subsequent ecological recovery following the cessation of the bloom. From this figure, it is clear that declines in overall species richness (*No species*) and in the diversity of specialist feeders (*No trop spec*), benthic-associated (*No benthic*) and estuarine spawning (*No est spawn*) species, in particular, drove the observed decrease in mean index score between the pre- and mid-bloom period.

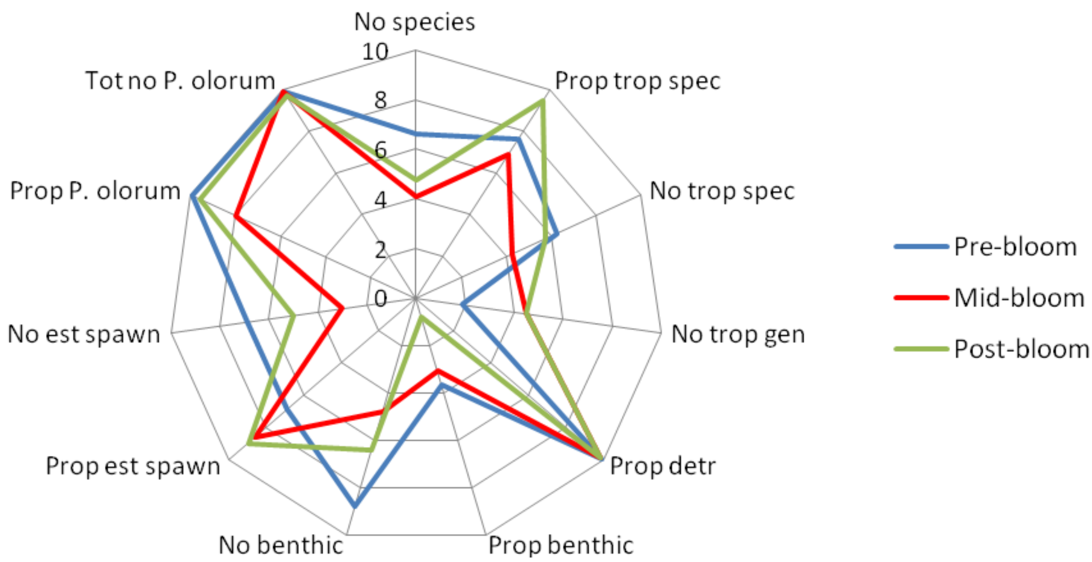


Figure 33. Example radar plot of mean nearshore fish metric scores recorded from sites throughout the CE zone before (pre), during (mid) and after (post) the *Karlodinium veneficum* bloom that occurred in this zone in May 2011. See Table 1 for a list of full metric names.

In addition to enabling the regular assessment and reporting of ecosystem condition via indices such as those outlined above, the quantitative data collected during the proposed fish community monitoring regime would be invaluable for facilitating broader, descriptive analyses of changes in fish community structure over longer temporal scales. Ideally, we recommend that regular annual monitoring using these indices would be complemented and strengthened by periodic (*e.g.* five-yearly/ten-yearly) analyses of observed long-term changes in the broader fish community data in response to longer-term drivers such as climate change and increasing population growth.

5.3. Further recommendations/opportunities

The above section provides a detailed account of the optimal design of a relatively low cost, future monitoring regime for the Fish Community Indices of estuarine condition. The implementation costs associated with a future monitoring regime could conceivably be reduced further by alterations to the proposed design, although it is crucial to note that such changes would likely reduce the reliability and utility of the index. Nonetheless, several potential modifications to the proposed design are outlined in Table 16, along with the practical, financial and science/management implications of these changes.

Table 16. Potential modifications to the proposed, optimal design for a monitoring regime, and their associated benefits and costs.

Modification	***Benefit***	***Costs***
- Sampling restricted to a single month in only one season (summer or autumn)	- Halving of financial costs associated with collecting and processing samples	- Reduced ability to detect and account for seasonal perturbations (*e.g.* algal blooms) - Reduced power to detect potential long-term shifts in seasonal effects resulting from climate change
- Sampling conducted biennially	- Halving of financial costs associated with collecting and processing samples	- Impaired ability to detect and interpret trends in estuary condition over time
- Monitoring incorporates the nearshore index only	- Considerable savings in time and financial costs	- Inability to correctly interpret changes in nearshore index scores, given the resulting lack of knowledge of adjacent, offshore waters - Incomplete assessment of estuarine condition

It is also important to note that the financial (labour) costs associated with implementing the proposed monitoring regime could be dramatically reduced if the field sampling and laboratory processing were conducted by personnel from within the university sector, rather than by government agency employees. Effective estuarine monitoring and management programs are increasingly characterised by cooperative partnerships between government agencies, local councils, university researchers and community groups (see, for example, South East Queensland's Ecosystem Health Monitoring Program and the Chesapeake Bay Program, USA). Under such a model, post-graduate students and research assistants could provide a cost-effective and highly skilled mechanism for the collection and analysis of monitoring data, whilst simultaneously providing opportunities to build science capacity and address gaps in our understanding of the ecology of the Swan-Canning Estuary.

Finally, the utility of these Fish Community Indices as a management tool could be maximised by further developing and integrating them as part of a broader approach to the monitoring and reporting of the condition of the Swan-Canning and other estuaries. The following points provide some potential directions by which this might be achieved.

- The data management and index calculation software could be more fully automated (and possibly integrated with existing water quality/phytoplankton reporting systems).
- Sampling under the proposed monitoring regime could provide a means of collecting fish for any potential future index of fish condition and/or contamination (Department of Health), and/or for studies of specific fish species, as may be required by the Department of Fisheries.
- The existing Fish Community Indices of estuarine condition developed for the brackish reaches of the Swan and Canning Rivers could be expanded and integrated with existing/proposed fish-based indices of the condition of their freshwater reaches and broader catchment (Department of Water).
- The broad-scale (zonal and system-wide) Fish Community Indices of estuarine condition for the Swan-Canning Estuary could be complemented by the development of condition indices based on benthic macroinvertebrate communities. The latter would provide a tool for quantifying estuarine condition on a more local (site-specific) scale.
- The fish-based indices could be incorporated into the ecosystem report cards which are currently under development for the Swan-Canning Estuary. These report cards should include indicators based on water quality, sediment and habitat quality, and different organism groups (*e.g.* fish, invertebrates, phytoplankton, seagrasses), thus providing a tool for holistic assessment and communication of estuarine condition.

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